THE EFFECTIVE APPROACH FOR PREDICTING VISCOSITY OF SATURATED AND UNDERSATURATED RESERVOIR OIL

A Dissertation

by

SAWIN KULCHANYAVIVAT

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2005

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	William D. McCain , Jr.
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ABSTRACT

The Effective Approach for Predicting Viscosity of Saturated and Undersaturated Reservoir Oil. (December 2005)

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Chair of Advisory Committee: Dr. William D. McCain, Jr.

Predicting reservoir oil viscosity with numerical correlation equations using field-measured variables is widely used in the petroleum industry. Most published correlation equations, however, have never profoundly realized the genuine relationship between the reservoir oil viscosity and other field-measured parameters. Using the proposed systematic strategy is an effective solution for achieving a high performance correlation equation of reservoir oil viscosity.

The proposed strategy begins with creating a large database of pressure-volume-temperature (PVT) reports and screening all possible erroneous data. The relationship between the oil viscosity and other field-measured parameters is intensively analyzed by using theoretical and empirical approaches to determine the influential parameters for correlating reservoir oil viscosity equations. The alternating conditional expectation (ACE) algorithm is applied for correlating saturated and undersaturated oil viscosity equations. The precision of field-measured PVT data is inspected by a data reconciliation technique in order to clarify the correctness of oil viscosity correlations. Finally, the performance of the proposed oil viscosity correlation equations is represented in terms of statistical error analysis functions.

The result of this study shows that reservoir oil density turns out to be the most effective parameter for correlating both saturated and undersaturated reservoir oil viscosity equations. Expected errors in laboratory-measured oil viscosity are the main factors that degrade the efficiency of oil viscosity correlation equations. The proposed correlation equations provide a reasonable estimate of reservoir oil viscosity; and their superior performance is more reliable than that of published correlation equations at any reservoir conditions.

DEDICATION

All of my success in this research study is dedicated to my parents for their love and support and to my family for their encouragement.

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Finally, I would like to thank Unocal Corporation for giving me a chance to learn the tasks of reservoir engineer and to obtain practical experience in the petroleum industry.

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CHAPTER I

INTRODUCTION

Reservoir oil viscosity is one of the important reservoir fluid properties used for many petroleum-engineering calculations such as evaluating hydrocarbon reserves, planning enhanced oil recovery methods, calculating fluid flowrate through reservoir rocks, etc. Therefore, achieving an accurate reservoir oil viscosity value is very crucial for petroleum engineers. Nowadays, viscosity of reservoir oil can be obtained by a laboratory PVT report and numerical correlation equations.

A PVT analysis report is the standard methodology for evaluating any fluid properties, but time and cost of oil viscosity investigation are huge obstructions for this method. Furthermore, the prior estimation of fluid properties is often required for advanced equipment design and well exploration. Therefore, the concept of numerical correlation equations has been proposed to the petroleum industry to alleviate all difficulties in viscosity determination and to predict viscosity of reservoir oil when a laboratory PVT report is not available. The advantages of this approach are not only to expedite the whole calculation process, but also to provide the values of predicted oil viscosity with high precision.

Several reservoir oil viscosity correlation equations have been widely used in the petroleum industry during the past decades. Most of them can be seen in many commercial types of software and can be used in reservoir simulation procedures. Generally, these oil viscosity correlation equations can be classified into three main categories based on reservoir conditions as follows:

This dissertation follows the style of the *JPT Journal.*

- Undersaturated oil viscosity correlation equations,
- Saturated oil viscosity correlation equations, and
- Dead oil viscosity correlation equations.

Undersaturated oil viscosity is defined as the reservoir oil viscosity at a pressure higher than the bubble point pressure at a given temperature. Saturated oil viscosity is the reservoir oil viscosity at and below the bubble point pressure at a given temperature. Dead oil viscosity is obtained when the pressure reaches the atmospheric pressure and no dissolved gas is left in the reservoir oil at a given temperature.

Several numerical correlation equations for estimating reservoir oil viscosity have been proposed in published literature since 1940. These published correlation equations can be categorized into two types based on the information that is required in computational methods. First, correlation equations based on material balance calculation use compositional information. Second, correlation equations based on empirical relationship require available field information to predict reservoir oil viscosity. Compositional information of reservoir oil is available in any complete PVT report, which always provides oil viscosity information. For this reason, viscosity correlation equations that need compositional data are redundant and unprofitable. Therefore, the purpose of this research is to concentrate on the correlation equations that use all available field-measured information to estimate reservoir oil viscosity.

After reviewing these publications, several questions have come up– for example, "What is the significance of reservoir parameters chosen for correlating viscosity of reservoir oil?", "Why do most publications propose the correlation equations that can be used efficiently only at some specific reservoir conditions?", and "Which of these correlations provide the most reliability for oil viscosity evaluation?" These questions are the motivation for this research, which aims to develop an effective approach for predicting viscosity of saturated and undersaturated reservoir oil.

In order to clarify these obscure questions, this research involves selecting influential parameters (to maximize the model accuracy) and developing simple correlation equations for reservoir oil viscosity that can be used for any reservoir conditions.

Chapter II reviews all available literature related to reservoir oil viscosity correlation equations. All numerical correlation equations provided in these papers are elaborately described in order to provide a background for this research.

Chapter III defines the objectives of this research and explains an effective approach that can be used for correlating the viscosity equations of saturated and undersaturated reservoir oil.

Chapter IV presents the overall information used to create a database that is used in this research, including the systematic procedures for database creation, data quality control processes, and tables of fluid properties for saturated and undersaturated reservoir oil.

Chapter V describes the relationship between reservoir oil viscosity and other parameters such as reservoir temperature, stock-tank oil gravity, solution gas-oil ratio, reservoir pressure, and oil density. Parameters that show the strong relationship with reservoir oil viscosity have a high potential to be used as influential parameters for correlating oil viscosity equations.

Chapter VI indicates the performance of oil viscosity correlation equations from various publications when they are applied to the database provided in this study. All correlation equations provide the performance in terms of statistical error analysis functions, average relative error (ARE) and absolute average relative error (AARE). Then the discussion of the results will be provided at the end of this chapter. Furthermore, graphical interpretations of calculated versus measured oil viscosities are also available in the appendices.

Chapter VII and VIII explain assumptions and methodologies for correlating saturated and undersaturated oil viscosity equations. A correlation analysis technique is used to evaluate the optimal combination among influential parameters that predict the most accurate reservoir oil viscosity. The quality of the data used to create oil viscosity correlation equations is also detected by using a data reconciliation technique.

Chapter IX validates the overall performance of proposed correlation equations at several reservoir conditions. The statistical error analysis results of the proposed and published correlation equations for saturated and undersaturated reservoir oil viscosities are compared and shown in graphical interpretations.

The conclusion of this study is summarized in Chapter X. **Appendix A** through **Appendix E** provides more information related to the corresponding sections throughout this dissertation.

CHAPTER II

LITERATURE REVIEW

The chronicle of oil viscosity correlation equations in the petroleum industry started more than five decades ago. A large number of mathematical equations have been introduced to predict viscosities of dead oil, saturated oil, and undersaturated oil by using all available field measurement information, for example, stock-tank oil gravity, solution gas-oil ratio, etc. Numerous published correlation equations are collected and summarized in this chapter to describe a development history of reservoir oil viscosity correlation equations and to represent the background of this research.

The History of Reservoir Oil Viscosity Correlation Equations

In 1946, Beal[1] published a well-known paper containing graphical methods for determining dead oil, saturated oil and undersaturated oil viscosities at high pressure and temperature. The author built a database by collecting reservoir fluid information from several oil fields in the United State. He mentioned that reservoir temperature, stock-tank oil gravity, solution gas-oil ratio, and reservoir pressure are the important parameters for correlating a viscosity of reservoir oil. Stock-tank oil gravity and reservoir temperature are the most effective variables for correlating a dead oil viscosity. No correlation equations are provided in this paper; but, later, the proposed graphical interpretation is fitted to achieve a precise numerical equation for reservoir oil viscosity[5].

In 1959, Chew and Connally[2] proposed a correlation equation and a graphical interpretation for saturated oil viscosity using 457 oil samples from the major producing areas of the United State, the Canada, and the South America. The authors believed that the relationship between saturated and dead oil viscosities, at constant solution gas-oil ratio, can be represented as a straight line on logarithmic coordinates. The concept of saturated oil viscosity correlation is described as follows:

Saturated oil viscosity correlation equation[2]

$$\mu_o = A \cdot \mu_{od}^{B} \text{, } \tag{1}$$

Generally, coefficients *A* and *B* could be represented as a function of solution gas-oil ratio. The adaptation of this concept has been widely used by several authors[3, 4, 5, 11, 20, 23, 27, 29] to create their saturated oil viscosity correlation equations.

In 1972, Aziz, Govier, and Fogarasi[3] modified the concept of Chew and Connally[2] to create a saturated oil viscosity correlation equation using 48 oil systems. Saturated oil viscosity can be calculated as follows:

Saturated oil viscosity correlation equation[3]

$$\begin{aligned} &\mu_o = A \cdot \mu_{od}^{B} \\ &A = 0.20 + (0.80 \cdot 10^{-0.00081 \cdot R_S}) \text{, } \\ &B = 0.43 + (0.57 \cdot 10^{-0.00072 \cdot R_S}) \end{aligned} \tag{2}$$

In 1975, Beggs and Robinson[4] used 600 oil systems, including 2,533 data points, to correlate saturated and dead oil viscosity equations. The authors proposed a dead oil viscosity correlation equation as a function of stock-tank oil gravity and reservoir temperature and they applied the concept of Chew and Connally[2] for correlating their saturated oil viscosity equation. The Beggs and Robinson correlation equation for saturated oil viscosity has become one of the most widely used correlation equations in the petroleum industry because they predict reservoir oil viscosity with some accuracy and cover a wide range of input information. Saturated and dead oil viscosities can be calculated as follows:

Dead oil viscosity correlation equation[4]

$$\mu_{od} = 10^{C} - 1$$
$$C = 10^{3.0324 - 0.02023 \cdot API} T^{-1.163} \quad , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Saturated oil viscosity correlation equation[4]

$$\mu_o = A \cdot \mu_{od}^{B}$$
$$A = 10.715 \cdot (R_S + 100)^{-0.515} \quad , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$
$$B = 5.44 \cdot (R_S + 150)^{-0.338}$$

In 1977, Standing[5] created correlation equations for predicting undersaturated and dead oil viscosities by applying a curve fitting method to the Beal[1] graphical correlation. The author modified the concept of Chew and Connally[2] correlation to create a new saturated oil viscosity correlation equation. The Standing correlation equations for predicting reservoir oil viscosities are interpreted as follows:

Dead oil viscosity correlation equation[5]

$$\mu_{od} = \left(0.32 + \frac{1.8 \cdot 10^{7}}{API^{4.53}}\right)\left(\frac{360}{T + 200}\right)^{D} \quad , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$
$$D = 10^{\left(0.43 + \frac{8.33}{API}\right)}$$

Saturated oil viscosity correlation equation[5]

$$\mu_o = A \cdot \mu_{od}^{B}$$
$$A = 10^{\left(2.2 \cdot 10^{-7} R_S - 7.4 \cdot 10^{-4}\right) R_S} \quad , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$
$$B = \left(\frac{0.65}{10^{8.62 \cdot 10^{-5} \cdot R_S}}\right) + \left(\frac{0.25}{10^{1.10 \cdot 10^{-3} \cdot R_S}}\right) + \left(\frac{0.062}{10^{3.74 \cdot 10^{-3} \cdot R_S}}\right)$$

Undersaturated oil viscosity correlation equation[5]

$$\mu_o = \mu_{ob} + 0.001(p - p_b)(0.024 \cdot \mu_{ob}^{1.6} + 0.038 \cdot \mu_{ob}^{0.56}) \text{,……..……….……...} \quad (7)$$

In 1980, Vasquez and Beggs[6] applied regression analysis techniques on more than 600 laboratory PVT reports to create an undersaturated oil viscosity correlation equation as a function of reservoir pressure, bubble point pressure, and bubble point oil viscosity. The authors recommended the Beggs and Robinson saturated oil viscosity correlation equation[4] for calculating bubble point oil viscosity. Further the authors used a large database to expand the range of input information in their correlation equation. The Vasquez and Beggs correlation equation is shown as follows:

Undersaturated oil viscosity correlation equation[6]

$$\begin{aligned} \mu_o &= \mu_{ob}\left(\frac{p}{p_b}\right)^E \\ E &= 2.6 \cdot p^{1.187} \exp\left(-11.513 - 8.98 \cdot 10^{-5} \cdot p\right) \end{aligned} \text{,…...……………..……….. } \quad (8)$$

In 1980, Glaso[7] used 26 oil samples from the North Sea to correlate a dead oil viscosity equation. The author proposed the dead oil viscosity correlation equation in terms of reservoir temperature and stock-tank oil gravity. The Glaso correlation equation usually has the similar performance with the Beggs and Robinson correlation equation[4]. The equation is indicated as follows:

Dead oil viscosity correlation equation[7]

$$\mu_{od} = 3.141 \cdot 10^{10} \cdot T^{-3.444} (\log API)^{10.313 \cdot \log(T) - 36.447} \text{,……..…...……….………...} \quad (9)$$

In 1983, Ng and Egbogah[8] presented two correlation equations for predicting a dead oil viscosity. For the first equation, the authors used nearly 400 laboratory PVT reports to modify the Beggs and Robinson dead oil viscosity correlation equation[4]. For the latter, the authors introduced a new parameter, which is a pour point temperature, in their correlation equation; but this concept is not handy since a pour point temperature is very difficult to measure and is not provided in a routine laboratory PVT report. The Ng and Egbogah correlation equations are presented as follows:

(1) Dead oil viscosity correlation equation[8]

$$\log\cdot\log(\mu_{od}+1) = 1.8653 - 0.025086\cdot API - 0.5644\log(T)\,, \ldots\ldots\ldots\ldots \quad (10)$$

(2) Dead oil viscosity correlation equation[8]

$$\begin{aligned}\log\cdot\log\,(\mu_{od}+1) &= -1.7095 - 0.0087917\cdot T_P + 2.7523\cdot API \\ &+ (-1.2943 + 0.0033214\cdot T_P + 0.958195\cdot API)\log\,(T - T_P)\end{aligned}\,, \ldots\ldots\ldots \quad (11)$$

In 1984, Sutton and Farshad[9, 10] evaluated the performance of several published oil viscosity correlation equations[1, 2, 4, 6, 7] by testing with 31 different oil samples from the Gulf of Mexico. The authors mentioned that the Glaso[7], the Beggs and Robinson[4], and the Vasquez and Beggs[6] correlation equations provide the best prediction for dead, saturated, and undersaturated oil viscosities in the Gulf of Mexico. The test results are provided in terms of statistical error analysis functions.

In 1987, Khan *et al*[11, 12] created a set of oil viscosity correlation equations using least square and regression analysis methods. Their equations were correlated using 75 oil samples from the Saudi Arabia. The authors tested the performance of their correlation equations with that of published correlation equations[1, 2, 4, 6, 7] in terms of statistical functions. The results indicate that their correlation equations provide a good estimation for the Saudi Arabia oil viscosity; but they require several input parameters which cause an inconvenient style of calculation. Saturated, bubble point, and undersaturated oil viscosity correlation equations are shown as follows:

Saturated oil viscosity correlation equation[11, 12]

$$\mu_o = \mu_{ob}\left(\frac{p}{p_b}\right)^{-0.14} \cdot \exp\left(-2.5 \cdot 10^{-4} \cdot (p - p_b)\right), \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Bubble point oil viscosity correlation equation[11, 12]

$$\mu_{ob} = \frac{0.09\sqrt{\gamma_g}}{\sqrt[3]{R_S}\left(\frac{T+459.67}{459.67}\right)^{4.5}(1-\frac{141.5}{API+131.5})^3}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Undersaturated oil viscosity correlation equation[11, 12]

$$\mu_o = \mu_{ob} \cdot \exp\left(9.6 \cdot 10^{-5} \cdot (p - p_b)\right), \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

In 1987, Al-Khafaji, Abdul-Majeed, and Hassoon[13] developed correlation equations for predicting dead, saturated, and undersaturated oil viscosities by using 300 oil samples from the Middle East region. The authors applied the Beal graphical correlation[1] for correlating a dead oil viscosity equation and modified the Chew and Connally correlation equation[2] with an extended range of solution gas-oil ratio for correlating a saturated oil viscosity equation. They also created a new undersaturated oil viscosity correlation equation as a function of stock-tank oil gravity, reservoir pressure, and bubble point pressure. The correlation equations are provided as follows:

Dead oil viscosity correlation equation[13]

$$\mu_{od} = \frac{10^{4.9563-0.00488\cdot T}}{\left(API + \frac{T}{30} - 14.29\right)^{2.709}} \quad ,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(15)}$$

Saturated oil viscosity correlation equation[13]

$$\begin{aligned}
&\mu_o = A \cdot \mu_{od}^B \\
&A = 0.247 + 0.2824\log R_S + 0.5657(\log R_S)^2 \\
&\quad -0.4065(\log R_S)^3 + 0.0631(\log R_S)^4 \qquad ,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(16)} \\
&B = 0.894 + 0.0546\log R_S + 0.07667(\log R_S)^2 \\
&\quad -0.0736(\log R_S)^3 + 0.01008(\log R_S)^4
\end{aligned}$$

Undersaturated oil viscosity correlation equation[13]

$$\begin{aligned}
&\mu_o = \mu_{ob} + 10^F \\
&F = -0.3806 - 0.1845\cdot API + 0.004034\cdot API^2 \quad ,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(17)} \\
&\quad -3.716\cdot 10^{-5}\cdot API^3 + 1.11\log(p - p_b)
\end{aligned}$$

In 1990, Abdul-Majeed, Kattan, and Salman[14] introduced a new correlation for predicting undersaturated oil viscosity. The equation was shown as a function of reservoir pressure, solution gas-oil ratio, and stock-tank oil gravity and it was developed using 41 oil samples from the North Africa and the Middle East. The correlation equation is directly derived from logarithmic coordinate that indicates a series of straight lines with a constant slope and varied intercepts; and these intercepts can be represented as a function of solution gas-oil ratio and stock-tank oil gravity. The Abdul-Majeed, Kattan, and Salman correlation equation is shown as follows:

Undersaturated oil viscosity correlation equation[14]

$$\mu_o = \mu_{ob} + 10^G$$
$$G = 1.9311 - 0.89941\ln(5.614 \cdot R_{Sb}) - 0.001194 \cdot API^2 \qquad ,............ (18)$$
$$+9.2545 \cdot 10^{-3} \cdot API \ln(5.614 \cdot R_{Sb}) - 5.2106 + 1.11\log(p - p_b)$$

In 1990, McCain[15] proposed a combination of the dead oil viscosity correlation equation of Ng and Egbogah[8] with the Beggs and Robinson[4] correlation equation for saturated oil viscosity, and the Vasquez and Beggs[6] correlation equation for undersaturated oil viscosity. The author also developed an effective graphical technique to determine oil viscosity information based on these published correlation equations.

In 1991, Kartoatmodjo and Schmidt[16] used several PVT reports from different geographical locations such as the Southeast Asia, the North America, the Middle East, and the Latin America, to modify the Glaso[7], the Chew and Connally[2], and the Standing[5] correlation equations for dead, saturated, and undersaturated oil viscosities, respectively. The Kartoatmodjo and Schmidt correlation equations are provided as follows:

Dead oil viscosity correlation equation[16]

$$\mu_{od} = 16.0 \cdot 10^8 \cdot T^{-2.5177} (\log API)^{5.7526\log(T) - 26.9718} \qquad ,…..……...………….. (19)$$

Saturated oil viscosity correlation equation[16]

$$\mu_o = -0.06821 + 0.9824 \cdot H + 0.0004034 \cdot H^2$$
$$H = \left(0.2001 + 0.8428 \cdot 10^{-0.000845 \cdot R_S}\right)\mu_{od}^{(0.43 + 0.5165 \cdot I)} \qquad ,…………...………...….. (20)$$
$$I = 10^{-0.00081 \cdot R_S}$$

Undersaturated oil viscosity correlation equation[16]

$$\mu_o = 1.00081 \cdot \mu_{ob} + 0.001127(p - p_b)(-0.006517 \cdot \mu_{ob}^{1.8148} + 0.038 \cdot \mu_{ob}^{1.590}) \qquad ,…... (21)$$

Later, the authors compared the performance of their modified correlation equations with that of published correlation equations in terms of average relative error, average absolute relative error, standard deviation, and coefficient of determination. The authors also used an unbiased database to test the quality of their correlation equations[17]. The results show that their modified correlation equations provide the best prediction for dead oil and saturated oil viscosities.

In 1991, Abu-Khamsin and Al-Marhoun[18] proposed a new alternative strategy for correlating a bubble point oil viscosity equation by using only a bubble point oil density as an input parameter. The correlation equation was created by applying nonlinear regression analysis on 62 oil samples from the Middle East and the Canada. The authors, however, did not mention about the application of their correlation equation for saturated and undersaturated reservoir oil. Theoretically, the typical shapes of oil viscosity and oil density show a similar trend for any reservoir pressures. From this reason, the Abu-Khamsin and Al-Marhoun correlation equation can be used to predict saturated and undersaturated oil viscosities. The correlation equation is provided as follows:

Bubble point oil viscosity correlation equation[18]

$$\mu_{ob} = \exp\left(-2.652294 + 8.484462 \cdot \rho_{ob}^{4}\right), \qquad (22)$$

In 1992, Labedi[19] introduced a set of oil viscosity correlation equations for predicting dead, saturated, undersaturated, and bubble point oil viscosities. The author selected a multiple regression analysis technique to correlate their equations by using about 100 oil samples from the Libya. Very interesting, a solution gas-oil ratio which is an important reservoir parameter was not included in the correlation equations. The author mentioned that the equations work very well with oil samples from the Libya and other geographical areas such as the Middle East, the North Sea, and some parts of America. The correlation equations should be used within a range of input data;

particularly, they should not be used if stock-tank oil gravity is less than 32 ^{o}API. The Labedi correlation equations are provided as follows:

Dead oil viscosity correlation equation[19]

$$\mu_{od} = \frac{10^{9.224}}{API^{4.7013} \cdot T^{0.6739}} \text{, ……………………………………………………….. (23)}$$

Saturated oil viscosity correlation equation[19]

$$\mu_o = \frac{\mu_{ob}}{1 - \left[\left(1 - \frac{p}{p_b}\right)\left(10^{-3.876} \cdot API^{1.1302} \cdot p_b^{0.5423}\right)\right]} \text{, …………………………………….. (24)}$$

Bubble point oil viscosity correlation equation[19]

$$\mu_{ob} = (10^{2.344 - 0.03542\,\gamma_o}) \frac{\mu_{od}^{0.6447}}{p_b^{0.426}} \text{, …………………………………………………… (25)}$$

Undersaturated oil viscosity correlation equation[19]

$$\mu_o = \mu_{ob} - \left[\left(1 - \frac{p}{p_b}\right)\left(\frac{10^{-2.488} \cdot \mu_{od}^{0.9036} \cdot p_b^{0.6151}}{10^{0.01976 \cdot API}}\right)\right] \text{, ………………………….. (26)}$$

In 1992, Bergman created two unpublished correlation equations for estimating dead and saturated oil viscosities (they were published by Whitson and Brule[20] in 1994). The author used the Beggs and Robinson[4] database plus some additional data to develop the equations. The concept of Chew and Connally correlation equation[2] was applied with this database in order to create a saturated oil viscosity correlation equation. The author claimed that the Beggs and Robinson dead oil viscosity correlation equation[4] could not work effectively when the reservoir temperature is less than 70 °F. The Bergman correlation equations are provided as follows:

Dead oil viscosity correlation equation[20]

$$\begin{aligned}\ln\cdot\ln(\mu_{od}+1) &= 22.33-0.194\cdot API+0.00033\cdot API^2 \\ &\quad -\left(3.20-0.0185\cdot API\right)\ln(T+310)\end{aligned} \quad ,\ldots\ldots\ldots\ldots \text{(27)}$$

Saturated oil viscosity correlation equation[20]

$$\begin{aligned}\mu_o &= A\cdot\mu_{od}^B \\ A &= \exp\left(4.768-0.8359\ln\left(R_S+300\right)\right), \ldots\ldots\ldots\ldots \text{(28)} \\ B &= 0.555+\frac{133.5}{R_S+300}\end{aligned}$$

In 1994, De Ghetto, Paone, and Villa[21, 22] introduced a novel strategy for correlating oil viscosity equations based on the different ranges of stock-tank oil gravity as follows:

- Extra heavy oil viscosity correlation equations ($API \leq 10$ °API)
- Heavy oil viscosity correlation equations ($10 < API \leq 22.3$ °API)
- Medium oil viscosity correlation equations ($22.3 < API \leq 31.1$ °API)
- Light oil viscosity correlation equations ($API > 31.1$ °API)

Furthermore, the authors tested the reliability of other published correlation equations[2, 4, 6, 7, 8, 15, 16, 19] using 195 oil samples collected from the Mediterranean Basin, the Africa, the Persian Gulf, and the North Sea. The best correlation equations for each oil gravity range and for the entire database were selected; and the numerical coefficients of these selected equations were recalculated by using multiple, linear, and nonlinear regressions. Noteworthy, the authors mentioned that the Non-Newtonian behavior of a highly viscous fluid could affect the reliability of laboratory measurement and the performance of viscosity correlation equations. The modified oil viscosity correlation equations are provided as follows:

Dead oil viscosity correlation equation[21, 22]

Extra heavy oil: Modified Ng and Egbogah's correlation equation[8]

$$\log\cdot\log(\mu_{od}+1)=1.90296-0.012619\cdot API-0.61748\log(T)\text{ ,……..… (29)}$$

Heavy oil: Modified Ng and Egbogah's correlation equation[8]

$$\log\cdot\log(\mu_{od}+1)=2.06492-0.0179\cdot API-0.70226\log(T)\text{ ,………… (30)}$$

Medium oil: Modified Kartoatmodjo's correlation equation[16]

$$\mu_{od}=220.15\cdot 10^{9}\cdot T^{-3.556}\log(API)^{12.5428\log(T)-45.7874}\text{ ,………..…………. (31)}$$

Light oil: Modified Ng and Egbogah's correlation equation[8]

$$\log\cdot\log(\mu_{od}+1)=1.67083-0.017628\cdot API-0.61304\log(T)\text{ ,………. (32)}$$

Entire oil samples: Modified Ng and Egbogah's correlation equation[8]

$$\log\cdot\log(\mu_{od}+1)=1.8513-0.025548\cdot API-0.56238\log(T)\text{ ,……..…. (33)}$$

Saturated oil viscosity correlation equation[21, 22]

Extra heavy oil: Modified Kartoatmodjo's correlation equation[16]

$$\mu_o = 2.3945 + 0.8927 \cdot H + 0.001567 \cdot H^2$$
$$H = \left(-0.0335 + 1.0785 \cdot 10^{-0.000845 \cdot R_S}\right)\mu_{od}^{(0.5798+0.3432 \cdot I)} \quad ,\ldots\ldots\ldots\ldots\ldots (34)$$
$$I = 10^{-0.00081 \cdot R_S}$$

Heavy oil: Modified Kartoatmodjo's correlation equation[16]

$$\mu_o = -0.6311 + 1.078 \cdot H - 0.003653 \cdot H^2$$
$$H = \left(0.2478 + 0.6114 \cdot 10^{-0.000845 \cdot R_S}\right)\mu_{od}^{(0.4731+0.5158 \cdot I)} \quad ,\ldots\ldots\ldots\ldots\ldots (35)$$
$$I = 10^{-0.00081 \cdot R_S}$$

Medium oil: Modified Kartoatmodjo's correlation equation[16]

$$\mu_o = 0.0132 + 0.9821 \cdot H - 0.005215 \cdot H^2$$
$$H = \left(0.2038 + 0.8591 \cdot 10^{-0.000845 \cdot R_S}\right)\mu_{od}^{(0.3855+0.5664 \cdot I)} \quad ,\ldots\ldots\ldots\ldots\ldots (36)$$
$$I = 10^{-0.00081 \cdot R_S}$$

Light oil: Modified Beggs and Robinson's correlation equation[4]

$$\mu_o = \left[25.1921(R_S + 100)^{-0.6487}\right]\mu_{od}^{2.7516(R_S+150)^{-0.2135}} \quad ,\ldots\ldots\ldots\ldots\ldots (37)$$

Entire oil samples: Modified Kartoatmodjo's correlation equation[16]

$$\mu_b = -0.032124 + 0.9289 \cdot H - 0.02865 \cdot H^2$$
$$H = \left(0.1615 + 0.7024 \cdot 10^{-0.000583 \cdot R_S}\right)\mu_{od}^{(0.172+0.7881 \cdot I)} \quad ,\ldots\ldots\ldots\ldots\ldots (38)$$
$$I = 10^{-0.000396 \cdot R_S}$$

Undersaturated oil viscosity correlation equation[21, 22]

Extra heavy oil: Modified Labedi's correlation equation[19]

$$\mu_o = \mu_{ob} - \left[\left(1 - \frac{p}{p_b}\right) \left(\frac{10^{-2.19} \cdot \mu_{od}^{1.055} \cdot p_b^{0.3132}}{10^{0.0099 \cdot API}} \right) \right], \ldots\ldots\ldots\ldots\ldots\ldots \text{(39)}$$

Heavy oil: Modified Kartoatmodjo's correlation equation[16]

$$\begin{aligned} \mu_o = {} & 0.9886 \cdot \mu_{ob} + \\ & 0.002763(p - p_b)(-0.01153 \cdot \mu_{ob}^{1.7933} + 0.0316 \cdot \mu_{ob}^{1.5939}) \end{aligned}, \ldots\ldots\ldots \text{(40)}$$

Medium oil: Modified Labedi's correlation equation[19]

$$\mu_o = \mu_{ob} - \left[\left(1 - \frac{p}{p_b}\right) \left(\frac{10^{-3.8055} \cdot \mu_{od}^{1.4131} \cdot p_b^{0.6957}}{10^{-0.00288 \cdot API}} \right) \right], \ldots\ldots\ldots\ldots\ldots\ldots \text{(41)}$$

Entire oil samples: Modified Labedi's correlation equation[19]

$$\mu_o = \mu_{ob} - \left[\left(1 - \frac{p}{p_b}\right) \left(\frac{10^{-1.9} \cdot \mu_{od}^{0.7423} \cdot p_b^{0.5026}}{10^{0.0243 \cdot API}} \right) \right], \ldots\ldots\ldots\ldots\ldots\ldots \text{(42)}$$

In 1995, Petrosky and Farshad[23] proposed viscosity correlation equations for dead, saturated, and undersaturated oil by using 126 laboratory PVT reports from the Gulf of Mexico. The authors used a nonlinear multiple regression analysis to create their correlation equations and used statistical error analysis functions to evaluate and compare the performance of their equations with that of published correlation equations[1, 2, 4, 6, 7, 8, 16]. Their dead and undersaturated oil viscosity correlation equations provide better results than the others. The authors claimed that their equations could be applied with reservoir oil from other regions of the world, but should be used inside a range of input data. Reservoir oil viscosities can be determined by using the following equations:

Dead oil viscosity correlation equation[23]

$$\begin{aligned} \mu_{od} &= 2.3511 \cdot 10^{7} \cdot T^{-2.10255} \log(API)^{J} \\ J &= 4.59388 \log(T) - 22.82792 \end{aligned} \quad ,\ldots\ldots\ldots \text{(43)}$$

Saturated oil viscosity correlation equation[23]

$$\begin{aligned} \mu_{o} &= A \cdot \mu_{od}^{B} \\ A &= 0.1651 + 0.6165 \cdot 10^{-6.0866 \cdot 10^{-4} \cdot R_S} \\ B &= 0.5131 + 0.5109 \cdot 10^{-1.1831 \cdot 10^{-3} \cdot R_S} \end{aligned} \quad ,\ldots\ldots\ldots \text{(44)}$$

Undersaturated oil viscosity correlation equation[23]

$$\begin{aligned} \mu_{o} &= \mu_{ob} + 1.3449 \cdot 10^{-3} (p - p_b) \cdot 10^{K} \\ K &= -1.0146 + 1.3322 \log(\mu_{ob}) - 0.4876 \log(\mu_{ob})^{2} - 1.15036 \log(\mu_{ob})^{3} \end{aligned} \quad ,\ldots\ldots \text{(45)}$$

In 1997, Almehaideb[24] created two oil viscosity correlation equations using a PVT database collected from 15 different reservoirs in the United Arab Emirates (UAE). The author used regression analysis methods to create viscosity correlation equations for saturated and undersaturated oil; and the performance of these correlation equations was compared with that of other published correlation equations[3, 4, 5, 6]. The author, however, never mentions about the application of these equations for other geographical regions; therefore, there is no guarantee that these correlation equations can be applied with oil samples outside the UAE. The saturated and undersaturated oil viscosity correlation equations are presented as follows:

Saturated oil viscosity correlation equation[24]

$$\mu_o = 6.59927 \cdot 10^5 \cdot R_S^{-0.597627} \cdot T^{-0.941624} \cdot \gamma_g^{-0.555208} \cdot API^{-1.487449} \text{ ,…………… (46)}$$

Undersaturated oil viscosity correlation equation[24]

$$\mu_o = \mu_{ob} \left(\frac{p}{p_b} \right)^L \text{ ,…………………… (47)}$$
$$L = 0.134819 + 1.94345 \cdot 10^{-4} \cdot R_{Sb} - 1.93106 \cdot 10^{-9} \cdot R_{Sb}^2$$

In 1997, Hanafy *et al.*[25] introduced a simple bubble point oil viscosity correlation equation based on 324 oil samples. The authors indicated that their correlation equation can predict reservoir oil viscosity at any specific reservoir pressure by inserting the corresponding value of oil density in the equation. The authors tested the performance of their equation with other published correlation equations[1, 2, 4, 6, 7, 11] and they inferred that their correlation equation provides the best prediction for reservoir oil viscosity. Very interesting, the concept of this work seems like the one proposed by Abu-Khamsin and Al-Marhoun[18] in 1991. The Hanafy *et al.* correlation equation is provided as follows:

Bubble point oil viscosity correlation equation[25]

$$\mu_{ob} = \exp(7.296 \cdot \rho_{ob}^3 - 3.095) \text{ ,……………………………………… (48)}$$

In 1998, Bennison[26] introduced a dead oil viscosity correlation equation for heavy oil in the North Sea. Only 16 data points which is the lowest number from the literature were used to develop a viscosity correlation equation in this paper. Because of the limited available data in this work, the author stated that this correlation equation is not practical to try and may not provide the high level of reliability for predicting dead oil viscosity of heavy oil. The Bennison correlation equation is shown as follows:

Dead oil viscosity correlation equation[26]

$$\mu_{od} = 10^{\left(0.10231 \cdot API^2 - 3.9464 \cdot API + 46.5037\right)} T^{\left(-0.04542 \cdot API^2 + 1.70405 \cdot API - 19.18\right)}, \quad (49)$$

In 1999, Elsharkawy and Alikhan[27] published viscosity correlation equations for dead, saturated, and undersaturated oil. Dead and saturated oil viscosity correlation equations from Beggs and Robinson[4] were modified with 254 oil samples from the Middle East. The authors developed an undersaturated oil viscosity correlation equation by using a multiple regression analysis and they introduced a new concept by using a dead oil viscosity as an input parameter. For the Middle East oil, the accuracy of calculated oil viscosity from this paper is better than that from other publications[4, 5, 6, 7, 16, 19]. The Elsharkawy and Alikhan viscosity correlation equations are as follows:

Dead oil viscosity correlation equation[27]

$$\log \cdot \log(\mu_{od} + 1) = 2.16924 - 0.02525 \cdot API - 0.68875 \log(T), \quad (50)$$

Saturated oil viscosity correlation equation[27]

$$\begin{aligned} \mu_o &= A \cdot \mu_{od}^B \\ A &= 1241.932(R_S + 641.026)^{-1.12410} \\ B &= 1768.841(R_S + 1180.335)^{-1.06622} \end{aligned}, \quad (51)$$

Undersaturated oil viscosity correlation equation[27]

$$\mu_o = \mu_{ob} + 10^{-2.0771}(p - p_b)(\mu_{od}^{1.19279} \cdot \mu_{ob}^{-0.40712} \cdot p_b^{-0.7941}), \ldots \quad (52)$$

In 2001, Elsharkawy and Gharbi[28] compared a classical regression technique with a modern concept of regression analysis which is the neural regression technique. The authors used both regression techniques to develop oil viscosity correlation equations based on 59 oil systems from the Kuwait. The authors mentioned that the oil viscosity correlation equation created by neural regression technique provides better performance than the equation developed by another regression technique. But the procedure of neural regression technique consists of several complicated steps and can not be performed without using of computer software. Therefore, a classical regression analysis technique is a preferable method for correlating oil viscosity equations. The oil viscosity correlation equations in this paper are shown as follows:

Dead oil viscosity correlation equation[28]

$$\log(\mu_{od}) = 10.7580 - 3.9145 \log(API) - 1.9364 \log(T), \ldots \quad (53)$$

Saturated oil viscosity correlation equation[28]

$$\mu_o = 10^{0.82604} \cdot p^{-0.38678} \cdot \mu_{od}^{0.79903}, \ldots \quad (54)$$

Undersaturated oil viscosity correlation equation[28]

$$\begin{aligned} \mu_o &= \mu_{ob} + M(p - p_b) \\ M &= \left(-5612 + 9481 \cdot \mu_{od} - 1459 \cdot \mu_{od}^2 + 81 \cdot \mu_{od}^3\right) \cdot 10^{-8} \end{aligned}, \ldots \quad (55)$$

In 2001, Dindoruk and Christman[29] used more than 90 PVT reports from the Gulf of Mexico regions to correlate dead, saturated, and undersaturated oil viscosity equations. Correlation equations in this paper were successfully developed by using the solver tool in Microsoft Excel and their performance were compared with the performance of the Standing[5] and the Petrosky and Farshad[23] correlation equations. Noticeably, besides of using stock-tank oil gravity and reservoir temperature, the bubble point pressure and the bubble point solution gas-oil ratio are also included in the dead oil viscosity correlation equation. The authors stated that their equations have a superior performance, provide a wide range of validity, and can be tuned for other geographical locations; but they contain up to 24 numerical coefficients and consist of several input parameters. The Dindoruk and Christman viscosity correlation equations are as follows:

Dead oil viscosity correlation equation[29]

$$\mu_{od} = \frac{9.36579 \cdot 10^{9} \cdot T^{-4.194017808} \log(API)^{14.505357625 \log(T) - 44.868655416}}{-3.1461171 \cdot 10^{-9} \cdot p_b^{4.740729 \cdot 10^{-4}} + 0.010433654 \cdot R_{Sb}^{-0.00077688}}, \ldots\ldots (56)$$

Saturated oil viscosity correlation equation[29]

$$\begin{aligned} \mu_o &= A \cdot \mu_{od}^{B} \\ A &= \frac{1}{\exp(4.740729 \cdot 10^{-4} \cdot R_S)} + \frac{-1.023451 \cdot 10^{-2} R_S^{0.6600358}}{\exp(1.07508 \cdot 10^{-3} \cdot R_S)} \quad , \ldots\ldots (57) \\ B &= \frac{1}{\exp(-2.191172 \cdot 10^{-5} \cdot R_S)} + \frac{-1.66098 \cdot 10^{-2} R_S^{0.4233179}}{\exp(-2.273945 \cdot 10^{-4} \cdot R_S)} \end{aligned}$$

Undersaturated oil viscosity correlation equation[29]

$$\begin{aligned} \mu_o &= \mu_{ob} + 6.334 \cdot 10^{-5} (p - p_b) \cdot 10^{O} \\ O &= 0.776644115 + 0.987658646 \log(\mu_{ob}) - 0.190564677 \log(R_{Sb}), \ldots\ldots (58) \\ &\quad + 9.147711 \cdot 10^{-3} \cdot \mu_{ob} \log(R_{Sb}) - 1.9111 \cdot 10^{-5} (p - p_b) \end{aligned}$$

The alternate version of reservoir oil viscosity correlation equations was proposed by Dexheimer, Jackson, and Barrufet[30] and Barrufet and Dexheimer[31]. These authors introduced a modification of two existing corresponding states compositional models for predicting an oil viscosity when the compositional information is not available. The modified correlation equations require reference fluid information, several computational procedures, and field-measured variables such as formation volume factor, solution gas-oil ratio and stock-tank oil gravity. The authors state that their correlation equations can be easily tuned and applied for any simulation software and they also provide better estimation than other correlation equations[11, 23].

Reservoir Field Parameters Used in Viscosity Correlation Equations

Knowing general reservoir parameters used for developing oil viscosity equations is very important for correlation developers; and they can use these parameters to develop a new correlation equation. The following tables provide field parameters that are used in all published oil viscosity correlation equations.

Table 1 shows reservoir parameters in published dead oil viscosity correlation equations. All correlation equations consist of reservoir temperature and stock-tank oil gravity, which correspond to the dead oil viscosity concept proposed by Beal[1].

Table 1- Reservoir parameters in published dead oil viscosity correlation equations

Author	T, °F	API, °API	p_b, psia	R_{Sb}, scf/STB
Beggs and Robinson	yes	yes		
Standing	yes	yes		
Glaso	yes	yes		
Ng and Egbogah	yes	yes		
Al-Khafaji, Abdul-Majeed, and Hassoon	yes	yes		
Kartoatmodjo and Schmidt	yes	yes		
Labedi	yes	yes		
Bergman	yes	yes		
De Ghetto, Paone, and Villa	yes	yes		
Petrosky and Farshad	yes	yes		
Bennison	yes	yes		
Elsharkawy and Alikhan	yes	yes		
Elsharkawy and Gharbi	yes	yes		
Dindoruk and Christman	yes	yes	yes	yes

Table 2 shows all reservoir parameters in published saturated oil viscosity correlation equations. The concept of Chew and Connally[2] by correlating a saturated oil viscosity equation as a function of dead oil viscosity and solution gas-oil ratio is used by most published correlation equations except for the Khan *et al*[11] and the Labedi[19] correlation equations.

Table 2- Reservoir parameters in published saturated oil viscosity correlation equations

Author	μ_{od}, cp	R_S, scf/STB	T, °F	API, °API	γ_g	p, psia	p_b, psia	μ_{ob}, cp
Aziz, Govier, and Fogarasi	yes	yes						
Beggs and Robinson	yes	yes						
Standing	yes	yes						
Khan *et al*						yes	yes	yes
Al-Khafaji, Abdul-Majeed, and Hassoon	yes	yes						
Kartoatmodjo and Schmidt	yes	yes						
Labedi				yes		yes	yes	yes
Bergman	yes	yes						
De Ghetto, Paone, and Villa	yes	yes						
Petrosky and Farshad	yes	yes						
Almehaideb		yes	yes	yes	yes			
Elsharkawy and Alikhan	yes	yes						
Elsharkawy and Gharbi	yes					yes		
Dindoruk and Christman	yes	yes						

Generally, saturated oil viscosity correlation equations can predict oil viscosity at and below the bubble point pressure; but some publications provide the specific correlation equations for predicting a bubble point oil viscosity. Very interesting, the Abu-Khamsin and Al-Marhoun[18] and the Hanafy *et al*[25] correlation equations require only a bubble point oil density to estimate a bubble point oil viscosity. **Table 3** provides reservoir parameters in all published bubble point oil viscosity correlation equations.

Table 3- Reservoir parameters in published bubble point oil viscosity correlation equations

Author	μ_{od}, cp	R_S, scf/STB	T, °F	API, °API	γ_g	p_b, psia	ρ_{ob}, lb/ft³
Khan *et al*		yes	yes	yes	yes		
Abu-Khamsin and Al-Marhoun							yes
Labedi	yes			yes		yes	
Hanafy *et al*							yes

Reservoir parameters in all published undersaturated oil viscosity correlation equations are provided in **Table 4**. Most of the authors recommend the readers about using their saturated oil viscosity correlation equations to estimate a bubble point oil viscosity which is an input parameter for all undersaturated oil viscosity correlation equations.

Table 4- Reservoir parameters in published undersaturated oil viscosity correlation equations

Author	μ_{ob}, cp	p, psia	p_b, psia	μ_{od}, cp	API, ^{o}API	R_{Sb}, scf/STB
Standing	yes	yes	yes			
Vasquez and Beggs	yes	yes	yes			
Khan *et al*	yes	yes	yes			
Al-Khafaji, Abdul-Majeed, and Hassoon	yes	yes	yes		yes	
Abdul-Majeed, Kattan, and Salman	yes	yes	yes		yes	yes
Kartoatmodjo and Schmidt	yes	yes	yes			
Labedi	yes	yes	yes	yes	yes	
De Ghetto, Paone, and Villa	yes	yes	yes	yes	yes	
Petrosky and Farshad	yes	yes	yes			
Almehaideb	yes	yes	yes			yes
Elsharkawy and Alikhan	yes	yes	yes	yes		
Elsharkawy and Gharbi	yes	yes	yes	yes		
Dindoruk and Christman	yes	yes	yes			yes

Summary

Reservoir parameters in oil viscosity correlation equations are summarized as follows:

- Reservoir temperature and stock-tank oil gravity have been used by all published dead oil viscosity correlation equations.
- The most often used parameters for correlating saturated oil viscosity equations in the literature are dead oil viscosity and solution gas-oil ratio.
- A bubble point oil density can be used to predict a bubble point oil viscosity.
- Reservoir pressure, bubble point pressure, and bubble point oil viscosity are used by all published undersaturated oil viscosity correlation equations.

CHAPTER III

OBJECTIVES

The objectives of this research result in a strong motivation to create the numerical correlation equations for estimating reservoir oil viscosity with high accuracy. The effective strategies proposed in this research are as follows:

- Create a wide range of fluid property database collected from several laboratory PVT reports for testing the performance of published correlation equations and for correlating new oil viscosity equations.
- Determine the effective variables for correlating reservoir oil viscosity equations based on the relationship between reservoir oil viscosity and influential reservoir parameters.
- Evaluate the performance of published viscosity correlation equations for saturated and undersaturated reservoir oil using a database provided in this study.
- Develop viscosity correlation equations for saturated and undersaturated reservoir oil using an effective correlation analysis technique.
- Validate the connection of oil viscosity at the bubble point pressure provided by the proposed saturated and undersaturated oil viscosity correlation equations.
- Achieve the optimal performance of the proposed oil viscosity correlation equations as represented in terms of statistical error analysis functions, ARE and AARE.
- Compare the performance of proposed oil viscosity correlation equations with that of published correlation equations in terms of statistical error analysis functions at several reservoir conditions.

CHAPTER IV

RESERVOIR FLUID PROPERTY DATABASE

More than three hundred PVT reports collected from worldwide geographical locations were originally anticipated to be used for developing saturated and undersaturated reservoir oil viscosity correlation equations in this research. Data quality control for reservoir fluid properties from these PVT reports, however, is the first mandatory step for correlation analysis and should be completed before correlating oil viscosity equations. The higher the quality of database, the better the performance of oil viscosity correlation will be achieved. Therefore, the most aspect of this chapter concentrates on the systematic procedures for creating database in order to acquire reliable and consistent PVT information. The quality control processes are provided as follows:

- Preparing a PVT Database for Correlation Analysis
- Identifying Errors from Typical Shape of Oil Viscosity
- Screening Data Sets for Multi-Stage Separator
- Checking Reliability of Solution Gas-Oil Ratio
- Determining Reservoir Oil Density
- Providing Fluid Properties Information for Database

Preparing a PVT Database for Correlation Analysis

The original database provided in this study was completely separated for saturated and undersaturated reservoir oil. For saturated reservoir oil, the database includes 380 different PVT reports with almost 3000 data points. And more than 3500 data points obtained from 318 PVT reports belongs to an undersaturated oil database. Assembling two databases together is required in order to achieve the completed database that consists of saturated and undersaturated oil information. Each PVT report from both databases is one-to-one matched using reservoir oil properties at the bubble point pressure to determine the connection and to verify the completion of PVT report. All unmatched PVT data sets are removed from an original database and kept separately.

After achieving the completed database, additional PVT reports are added into the database to expand the range of reservoir oil viscosity. The new database consists of 218 completed PVT reports with 1,348 data points for saturated reservoir oil and 2,329 data points for undersaturated reservoir oil. Before correlating reservoir oil viscosity equations, this database definitely requires more quality control processes to improve their quality and to provide the best performance for correlating oil viscosity equations.

Identifying Errors from a Typical Shape of Oil Viscosity

Reservoir oil viscosity is used as the dependent variable in regression analysis for saturated and undersaturated oil viscosity correlation equations. To minimize any potential errors in viscosity data, all data sets must provide the following typical shape of oil viscosity as provided in **Fig. 1**. Above the bubble point pressure, reservoir oil viscosities decrease almost linearly as pressure decreases[15] because the compression on liquid molecules is reduced at lower pressure. The reduction of compressive force causes a steady increase in the mobility of liquid molecules, which resulting the decrease in oil viscosity. On the other hand, below the bubble point pressure, the change of liquid composition causes a large increase in reservoir oil viscosity. On the basis of the gravitational effect, the gas released from the solution takes the smaller molecules, leaving large complex molecules in the remaining reservoir liquid[15]. The low mobility of large liquid molecules causes the increase in the reservoir oil viscosity. This phenomenon is always applied for all kinds of oil viscosity in the reservoir. Therefore, saturated and undersaturated reservoir oil viscosities from the database should provide a similar typical shape.

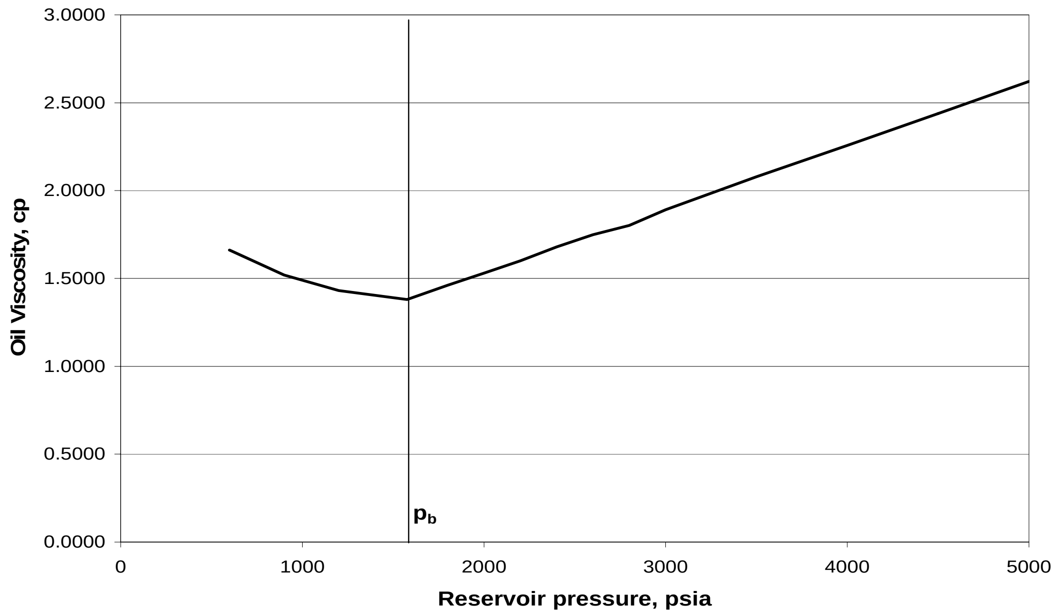

Fig. 1- Typical shape of reservoir oil viscosity as a function of pressure at constant reservoir temperature.

After screening all data set, five PVT reports show an inconsistent configuration with a typical shape of oil viscosity and need to be removed from the database. **Fig. 2** shows two examples of removed data sets. For data set A, the entire data set is removed because all undersaturated oil viscosity values behave differently from a typical shape. For data set B, the big shift near the bubble point pressure causes a large error in this data set.

Outlying data points found from 8 PVT reports are considered as bad data points and they are removed from the database to maintain the quality. Examples of outlying data points, as shown in **Fig. 3**, clearly indicate two improper data points of undersaturated oil viscosity in this plot.

After identifying errors from typical shape of oil viscosity, the database consists of 213 completed PVT reports. All data sets that pass this error screening basis still need to be tested with other quality control techniques. Checking data consistency and reliability is the next important procedure before processing with a regression routine.

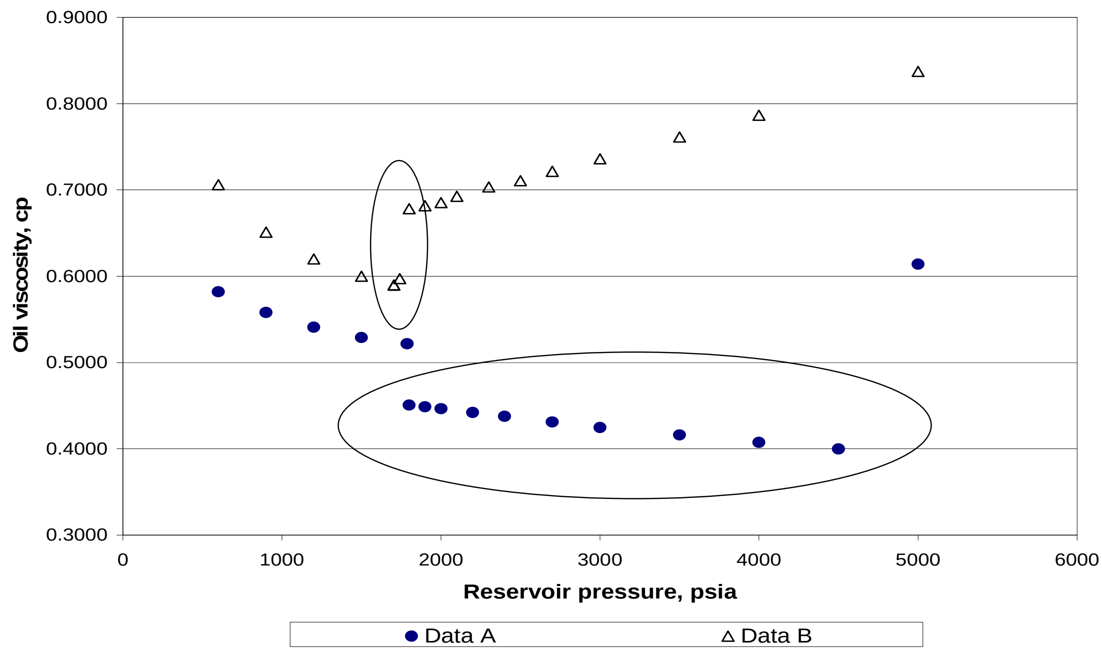

Fig. 2- Removed data sets due to inconsistent shape of oil viscosity.

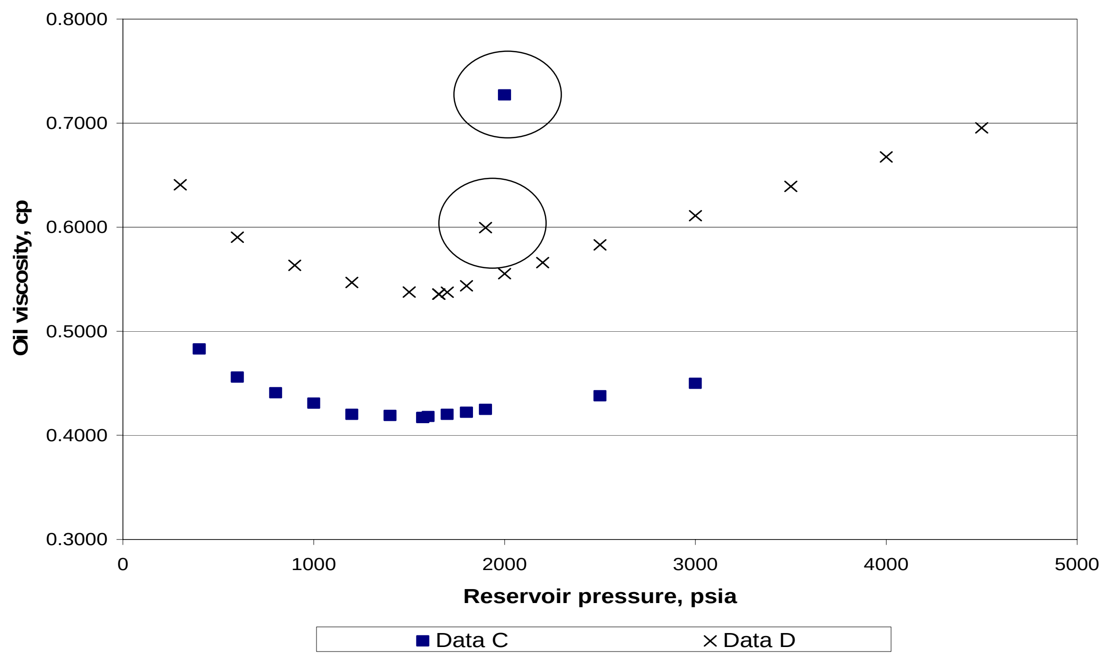

Fig. 3- Removed data points due to inconsistent shape of oil viscosity.

Screening Data Sets for Multi-stage Separation

Two-stage separation, including one separator and one storage tank, is normally used for black oil systems with optimum separator pressure of 100 to 120 psig at normal temperature[15]. For some cases, three- or four-stage separation can be performed to maximize the oil recovery when fluid has high solution gas-oil ratio or oil gravity[32]. Fluid property information for multi-stage separation is identical for compositional measurement, flash vaporization, differential liberation, and oil viscosity measurement; but fluid property information for separator tests is provided individually based on the number of separator used in the field. For example, three-stage separation provides two different sets of solution gas-oil ratio, oil formation volume factor, and separator gas specific gravity information. Certainly, data sets involving multi-stage separation always provide the duplicate information of reservoir oil viscosity and other parameters. Therefore, these imitated data must be carefully inspected and removed from the database.

The screening results indicate 13 three-stage separations and 2 four-stage separations. Fluid properties provided in these data sets, for example, oil viscosity, reservoir pressure, reservoir temperature, etc, are identical except those from separator tests. To verify which PVT information could be used in the database, each data set must be tested with correlation equations for bubble point pressure and oil formation volume factor; and data sets that provide the most comparable results between calculated and laboratory-measured values would be kept in the database.

After screening PVT data sets of 15 multi-stage separations, only 11 PVT data sets show the robust consistence between calculated and laboratory-measured fluid properties. Unreliable PVT reports are removed from a database and kept in the separate file. The database at this stage consists of 192 complete PVT reports. Before finalizing the database, the last step of data preparation is checking the reliability of solution gas-oil ratio that obtains from differential liberation and separator tests.

Checking Reliability of Solution Gas-oil Ratio

Empirically, the values of solution gas-oil ratio at the bubble point pressure from differential vaporization are higher than those from separator tests. For some instances, bubble point solution gas-oil ratio from separator tests can be larger if the values less than 200 scf/STB are achieved. To ensure the database reliability, every single data set requires a verification of solution gas-oil ratio profiles according to the proposed criteria.

After checking the entire database, 9 PVT data sets violate empirical criteria and have to be removed from the database. The finalize database for correlating reservoir oil viscosity equations consists of 183 completed PVT reports with 1,118 observations for saturated reservoir oil and 1,968 observations for undersaturated reservoir oil.

Determining Reservoir Oil Density Information

Reservoir parameters listed in **Table 1** to **Table 4** are required for correlating reservoir oil viscosity equations. Reservoir oil density data, however, are not available in several PVT data sets and is one of important PVT parameters that need in this research. To recover the missing information of saturated and undersaturated reservoir oil densities, using the high performance oil density correlation equations provided in the literature is totally necessary and definitely helpful.

In 1995, McCain and Hill[33] created a set of correlation equations for predicting oil density at and below the bubble point pressure by using a large database. Their correlation equations provide very accurate results, which predicting reservoir oil densities within ±4 percent. Because of the high level of performance and quality, therefore, the McCain and Hill correlation equation is selected to determine all missing reservoir oil density in this research. Several computational procedures are required to receive the density of saturated reservoir oil; and the first step is to calculate a pseudoliquid density, ρ_{po}, at standard conditions by recombining the surface liquid and surface gas as follows:

Pseudoliquid density correlation equation at standard conditions[33]

$$\rho_{po} = \frac{R_S \cdot \gamma_g + 4600 \cdot \gamma_o}{73.71 + \dfrac{R_S \cdot \gamma_g}{\rho_a}}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(59)}$$

Eq. 59 requires the simple laboratory-measured parameters and the apparent liquid density, ρ_a, which is the density of the surface gas if it were liquid before[33]. The apparent liquid density correlation equation is as follows:

Apparent liquid density correlation equation[33]

$$\begin{aligned}\rho_a = &-49.8930 + 85.0149 \cdot \gamma_g - 3.70373 \cdot \gamma_g \cdot \rho_{po} \\ &+ 0.047981 \cdot \gamma_g \cdot \rho_{po}^2 + 2.98914 \cdot \rho_{po} - 0.035688 \cdot \rho_{po}^2\end{aligned}, \ldots\ldots\ldots\ldots\ldots \text{(60)}$$

An iteration procedure is required for the use of **Eq. 59** and **Eq. 60** since both parameters are involved with each other. The first trial value of ρ_{po} may be obtained by the following equation:

$$\rho_{po} = 52.8 - 0.01 \cdot R_{Sb}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(61)}$$

The authors stated that successful substitution is very stable and should converge within 5 trials. Then converged pseudoliquid density is adjusted from standard condition to reservoir pressure by using the equation[5, 34] as follows:

$$\begin{aligned}\rho_{bs} = \rho_{po} &+ \left[0.167 + 16.181 \cdot 10^{-0.0425 \cdot \rho_{po}}\right]\left(\frac{p}{1000}\right) \\ &- 0.01\left[0.299 + 263 \cdot 10^{-0.0603 \cdot \rho_{po}}\right]\left(\frac{p}{1000}\right)^2\end{aligned}, \ldots\ldots\ldots\ldots\ldots \text{(62)}$$

The density of reservoir oil at reservoir condition, ρ_o, can be obtained after adjusting the density to reservoir temperature by the following equation[35]:

Saturated reservoir oil density correlation equation[33]

$$\begin{aligned}\rho_o = \rho_{bs} &- \left[0.00302 + 1.505 \cdot \rho_{bs}^{-0.951}\right](T-60)^{0.938} \\ &+ \left[0.0233 \cdot 10^{-0.0161 \cdot \rho_{bs}}\right](T-60)^{0.475}\end{aligned}, \qquad (63)$$

The next step is to determine the density of undersaturated reservoir oil. As pressure above the bubble point, the oil density can be calculated according to the definition of the coefficient of isothermal compressibility, c_o, of a liquid above the bubble point pressure[15]. The equation is as follows:

$$c_o\left(p - p_b\right) = \ln\left(\frac{\rho_o}{\rho_{ob}}\right), \qquad (64)$$

The use of bubble point oil density is required and can be computed using the McCain and Hill[33] technique. **Eq. 64** can be applied with the flash vaporization data, which is the relative volume, $(V_t/V_b)_F$. The equation for an average value of oil compressibility between reservoir pressure and bubble point pressure as a function of relative volume is as follows:

$$c_o\left(p_b - p\right) = \ln\left(V_t / V_b\right)_F, \qquad (65)$$

Substituting **Eq. 65** into **Eq. 64** and rearranging these equations are performed in order to achieve an undersaturated oil density equation as a function of bubble point oil density and relative volume. The undersaturated oil density equation is as follows:

Undersaturated reservoir oil density equation

$$\rho_o = \frac{\rho_{ob}}{\left(V_t / V_b \right)_F} , \ldots\ldots (66)$$

After fulfilling saturated and undersaturated reservoir oil density information, the database is ready to be used for correlating oil viscosity equations in this research.

Providing Tables of Fluid Properties Information

Table 5 shows a wide range database used in this research for saturated reservoir oil. In addition, statistical information, symbols, and units of all fluid properties are provided for more details. **Table 6** gives all similar information for undersaturated reservoir oil. The range of oil viscosity in this research, which is 0.167 to 279.83 cp, covers from light oil to heavy oil.

Table 5- Fluid properties information for saturated reservoir oil (183 PVT reports/1118 data points)

Reservoir parameters	Symbol	Unit	Min	Median	Mean	Max
Reservoir pressure	p	psia	27	1100.5	1274.7	5297
Reservoir temperature	T	°F	107	198	199	320
Stock-tank oil gravity	*API*	°API	15.8	35.6	35.5	57.7
Separator gas specific gravity	γ_g		0.6506	0.8389	0.8775	1.9161
Solution gas-oil ratio	R_S	scf/STB	4	288	351	1534
Bubble point solution gas-oil ratio	R_{Sb}	scf/STB	12	558	565	1534
Reservoir oil viscosity	μ_o	cp	0.1670	0.7225	4.19	157.60
Reservoir oil density	ρ_o	lb/cu ft	34.27	46.30	46.40	57.42

Table 6- Fluid properties information for undersaturated reservoir oil (183 PVT reports/1968 data points)

Reservoir parameters	Symbol	Unit	Min	Median	Mean	Max
Reservoir pressure	p	psia	106	2700	2734.8	7500
Reservoir temperature	T	°F	107	196	199	320
Stock-tank oil gravity	*API*	°API	15.8	34.3	33.8	57.7
Separator gas specific gravity	γ_g		0.6506	0.8635	0.8966	1.9161
Bubble point solution gas-oil ratio	R_{Sb}	scf/STB	12	350	435	1534
Oil formation volume factor	B_o	res bbl/STB	1.0005	1.2199	1.2617	2.0440
Relative volume	$(V_t/V_b)_F$		0.9079	0.9934	0.9894	1.0000
Reservoir oil viscosity	μ_o	cp	0.1670	0.8408	10.21	279.83
Reservoir oil density	ρ_o	lb/cu ft	34.27	46.46	46.89	58.30

CHAPTER V

DETERMINING EFFECTIVE PARAMETERS

This chapter focuses mainly on the relationship between the dependent variable which is reservoir oil viscosity and several independent variables, for example, reservoir temperature, stock-tank oil gravity, reservoir oil density, etc. The stronger bonding among these reservoir variables causes the better performance of oil viscosity correlation equations in this study. Most of laboratory-measured parameters provided in **Table 1** to **Table 4** has been intensively studied and has been evaluated for the possibility of being used as effective independent variables in correlation of oil viscosities.

Generally, reservoir temperature and pressure are the main factors that affect reservoir oil viscosity. For the effect of reservoir temperature, the amount of heat applied on reservoir fluid weakens an intermolecular force and agitates the mobility of liquid molecule, which results a reduction of liquid viscosity in the reservoir. Therefore, an increase in reservoir temperature will reduce the liquid viscosity. The effect of reservoir pressure on reservoir oil viscosity has been described in the previous chapter. The solution gas-oil ratio, which is a direct function of reservoir pressure, is also considered as a third parameter that affects oil viscosity[15]. The origin of the relationship between the reservoir oil viscosity and other reservoir parameters, however, has never been appeared in any publications. Hence, the uses of reservoir parameters for correlating oil viscosity equations in the literature are totally questionable and there is a need to clarify the exact relationship of these reservoir parameters with reservoir oil viscosity.

Unveiling the mystery of fluid property relationship is provided in this research. To serve this purpose, the relationship between the dependent variable and each independent variable is revealed in this chapter by using both theoretical and empirical strategies. The details of these systematic analytical procedures are provided in the following discussion.

Comparing Typical Shape of Oil Viscosity with Other Reservoir Parameters

Comparing the typical shape of reservoir oil viscosity, as shown in **Fig. 1**, with typical shapes of reservoir temperature, stock-tank oil gravity, solution gas-oil ratio, reservoir pressure, and reservoir oil density is an effective theoretical approach to demonstrate the fundamental relationship between reservoir oil viscosity and other reservoir parameters.

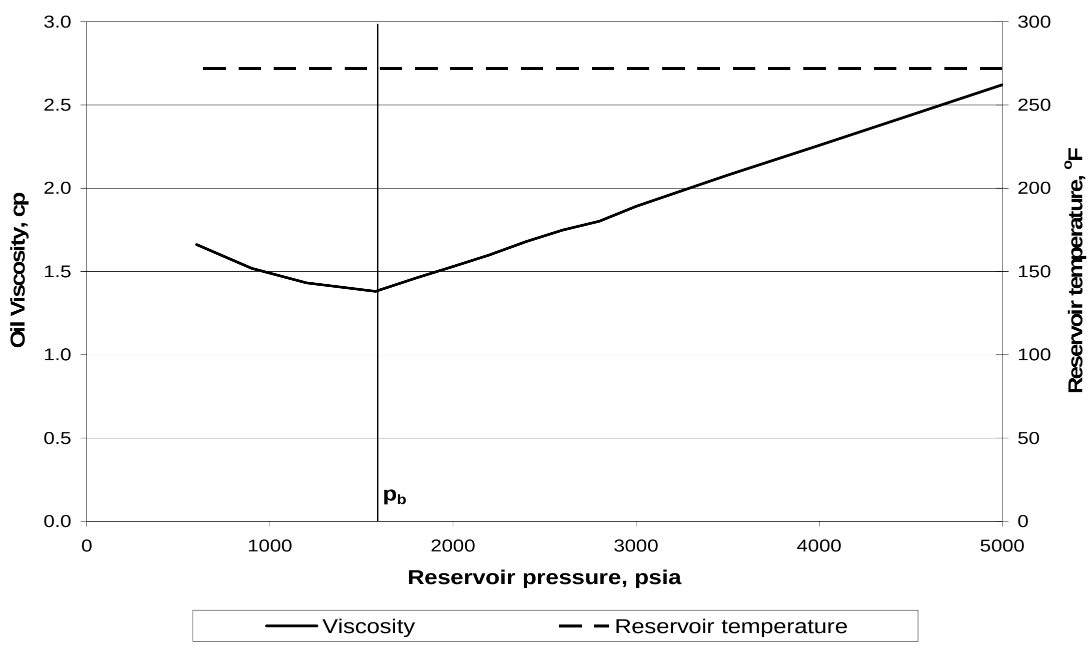

Fig. 4- Relationship between reservoir oil viscosity and reservoir temperature for saturated and undersaturated reservoir oil.

Generally, reservoir temperature is considered as a constant parameter; and, therefore, a typical shape of reservoir temperature is drawn as a horizontal straight line and does not show any relationship with a typical shape of reservoir oil viscosity, as shown in **Fig. 4**. From this reason, reservoir temperature probably has a small effect on saturated and undersaturated oil viscosities and it could be a low potential reservoir parameter for correlating oil viscosity equations. The influence of reservoir temperature, however, could apply on dead oil viscosity at the atmospheric pressure.

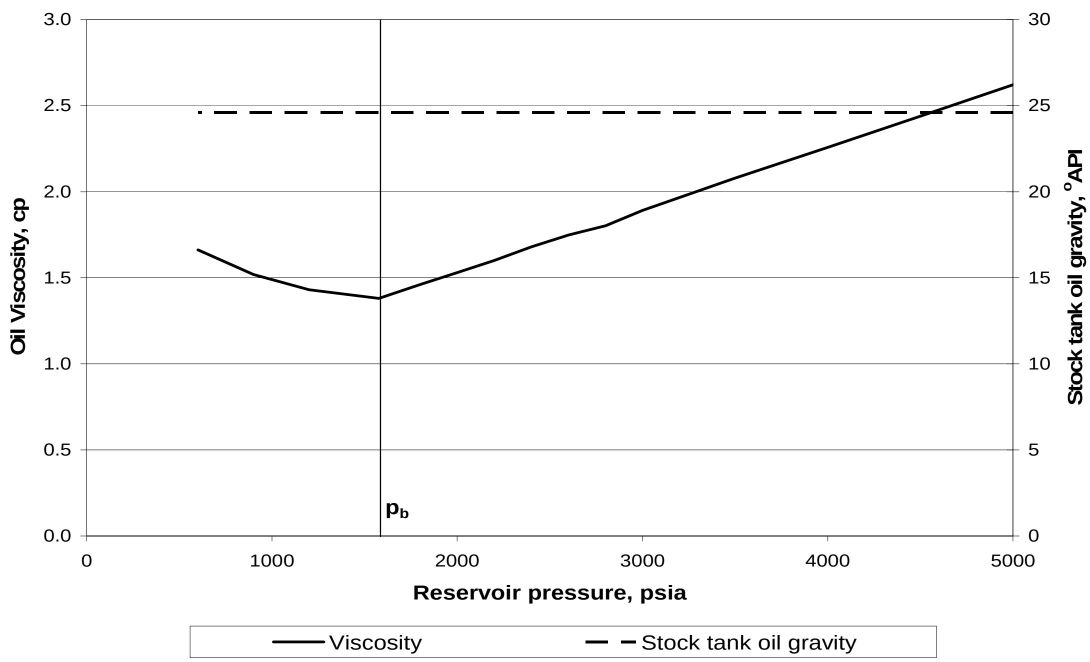

Fig. 5- Relationship between reservoir oil viscosity and stock-tank oil gravity for saturated and undersaturated reservoir oil.

Because of sampling at standard condition, stock-tank oil gravity does not depend on reservoir pressure and is presented as a horizontal straight line on a typical shape. Again, no relationship between reservoir oil viscosity and stock-tank oil gravity is indicated in **Fig. 5**. Based on a graphical interpretation, stock-tank oil gravity is probably not a potential parameter for correlating saturated and undersaturated oil viscosity equations; but it may uses effectively for correlating a dead oil viscosity equation.

By definition, dead oil viscosity is a viscosity of gas-free reservoir oil at the atmospheric pressure and the reservoir temperature. Therefore, reservoir temperature is not only a direct function of dead oil viscosity but also stock-tank oil gravity that shows the relationship with dead oil viscosity because it is measured at the atmospheric pressure. Both parameters are the effective parameters for correlating a dead oil viscosity equation and they have been seen in all published correlation equations as provided in **Table 1**.

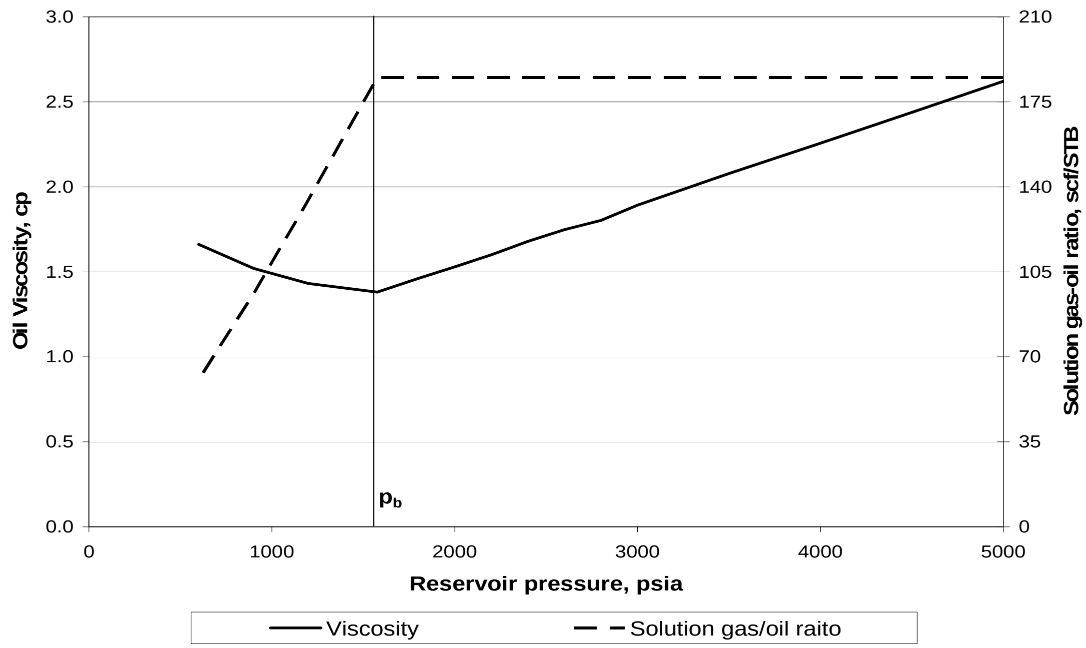

Fig. 6- Relationship between reservoir oil viscosity and solution gas-oil ratio for saturated and undersaturated reservoir oil.

The typical shape of solution gas-oil ratio is completely separated for saturated and undersaturated reservoir oil as shown in **Fig. 6**. For undersaturated reservoir oil, there is no change in the amount of gas in solution from the initial reservoir pressure to the bubble point pressure, which indicates a horizontal straight line on a typical shape. Therefore, a solution gas-oil ratio has no relationship with an undersaturated oil viscosity and is not a potential parameter for correlating an undersaturated oil viscosity equation.

For saturated reservoir oil, the decrement in solution gas-oil ratio is a function of reservoir pressure; because a large amount of gas in solution is released from a liquid when reservoir pressure drops below the bubble point. The remaining liquid is packed with lot of large and complex molecules causing a substantial increase in saturated oil viscosity. Therefore, a decrement in solution gas-oil ratio causes an increasing in oil viscosity. This relationship logically supports the appearance of solution gas-oil ratio in several published saturated oil viscosity correlation equations. Hence, solution gas-oil ratio is considered as an effective parameter for correlating a saturated oil viscosity equation.

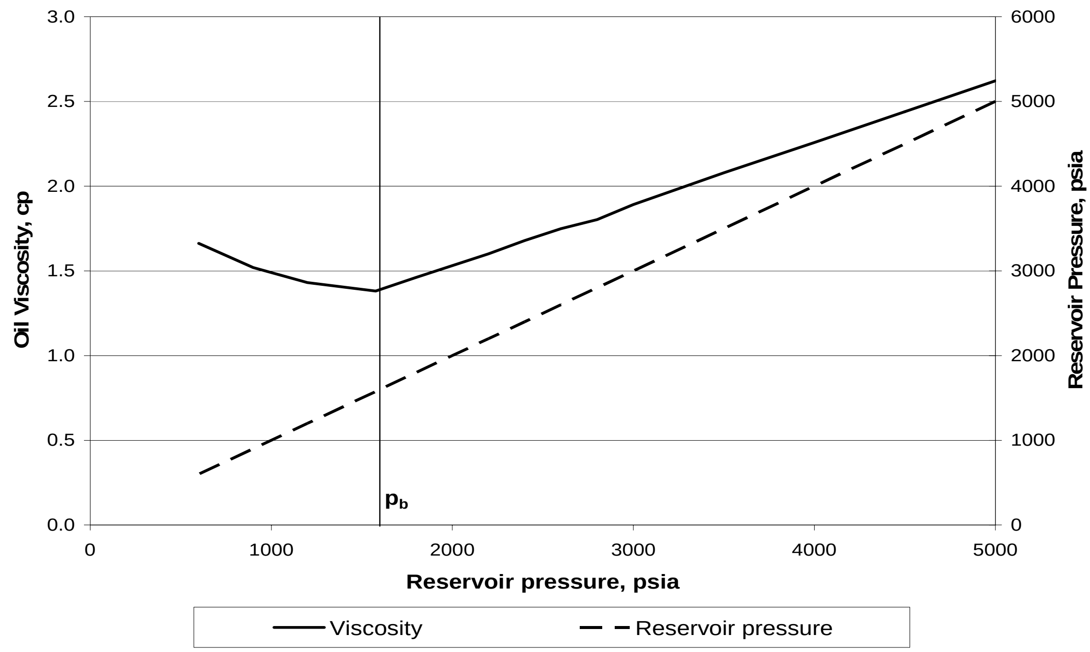

Fig. 7- Relationship between reservoir oil viscosity and reservoir pressure for saturated and undersaturated reservoir oil.

The typical shapes of reservoir pressure and reservoir oil viscosity are shown in **Fig. 7**. For undersaturated reservoir oil, an initial reservoir pressure provides a strong intermolecular force on liquid molecules, which results a high viscosity value. Later, a decrement in oil compressibility, while initial reservoir pressure drops to the bubble point pressure, reduces an intermolecular force, which causes a reduction in oil viscosity. This phenomenon represents a relationship between both parameters; but, in all published correlation equations, reservoir pressure has never been used individually and always associates with bubble point pressure as shown in pressure function, which is either pressure difference (p-p_b) or pressure ratio (p/p_b).

For saturated reservoir oil, the effect of oil compressibility is no longer applied on saturated oil viscosity because the decrement of reservoir pressure below the bubble point does not cause the reduction in oil viscosity anymore. From another standpoint, the main factor that affects on the increment of saturated oil viscosity is a solution gas-oil ratio. Therefore, reservoir pressure is possibly not the best independent variable for correlating a saturated oil viscosity equation in this research.

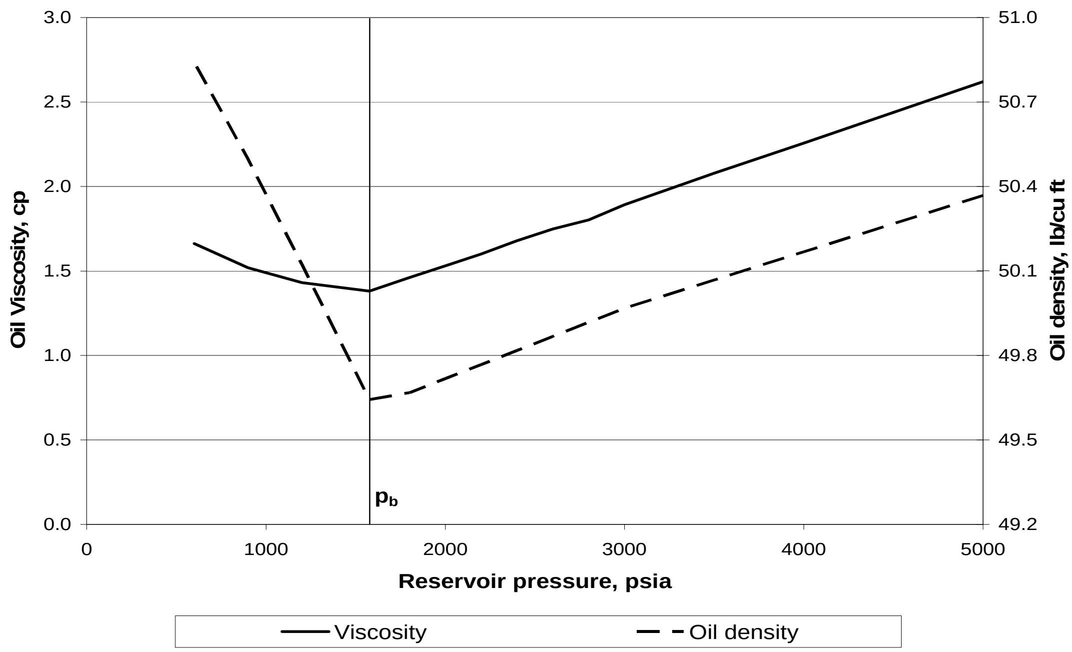

Fig. 8- Relationship between reservoir oil viscosity and reservoir oil density for saturated and undersaturated reservoir oil.

Reservoir oil density is the last parameter which is studied in this part. The typical shapes of viscosity and density of reservoir oil show a strong relationship for both saturated and undersaturated reservoir oil as provided in **Fig. 8**. Generally, the factors that provide the impact on reservoir oil viscosity could cause the similar effect on reservoir oil density. For example, the compressibility effect in liquid molecules for undersaturated reservoir oil changes both oil viscosity and oil density in the same manner; and, for saturated reservoir oil, a decrement in the amount of gas in solution also causes an increment in both parameters. According to this imitate behavior; reservoir oil density could possibly be the most effective parameters for correlating saturated and undersaturated oil viscosity equations.

Although reservoir oil density provides a robust relationship with reservoir oil viscosity, the use of this parameter, however, is ignored by the equations from most publication. Therefore, the new concept for correlating reservoir oil viscosity equations by using reservoir oil density and other reservoir parameters is purposed in this research study.

Plotting Reservoir Oil Viscosity Against Field-measured Parameters

An empirical approach for evaluating the effective parameters for viscosity correlation equations is provided to support the assumption that made in the previous part. By plotting the reservoir oil viscosity against other reservoir parameters, the trend of the plots could imply the interrelation between these parameters. The database, including 183 completed PVT reports, is used to conduct this approach. The plots are separated for saturated and undersaturated reservoir oil in order to clarify the trend of reservoir parameters for each type of reservoir oil.

For saturated oil reservoir, oil viscosity is plotted against reservoir temperature, stock-tank oil gravity, solution gas-oil ratio, and reservoir oil density as shown in **Fig. 9** through **Fig. 12**. Reservoir temperature and stock-tank oil gravity are the best parameters for correlating a dead oil viscosity equation. Testing both parameters, however, is performed in this part to find out whether they possibly have an effect on saturated oil viscosity. Solution gas-oil ratio and reservoir oil density are also tested to support the assumption that they are the potential parameters for correlating a saturated oil viscosity equation.

To present a reasonable interpretation of the plots, saturated oil viscosity is plotted in a logarithmic coordinate while other parameters are plotted in a Cartesian coordinate. The plot of saturated oil viscosity against reservoir temperature is shown in **Fig. 9**. A tremendous scattering of the data indicates a weak relationship between these parameters and confirms an unprofitable use of reservoir temperature for correlating a saturated oil viscosity equation. From this reason, reservoir temperature is not the main contributor for the accuracy of saturated oil viscosity correlation equations.

The plot of oil viscosity versus stock-tank oil gravity provides some relationships as shown in **Fig. 10**. Theoretically, stock-tank oil gravity is a direct function of stock-tank oil density; and reservoir oil density indicates a strong relationship with reservoir oil viscosity. Therefore, one can imply that both stock-tank oil gravity and stock-tank oil density could have some relationship with saturated oil viscosity. Although there is some scattering in this plot, the trend of the plot indicates that an increment in stock-tank oil gravity causes a reduction in saturated oil viscosity. Hence stock-tank oil gravity could possibly be a potential independent variable for correlating not only dead oil viscosity but also saturated oil viscosity equations.

A relationship between saturated oil viscosity and solution gas-oil ratio, as presented in **Fig. 11**, indicates that a decrement in solution gas-oil ratio causes an increment in saturated oil viscosity, which follows the theoretical explanation in the previous section. A tremendous increment of oil viscosity at low solution gas-oil ratio, for the values less than 150 scf/STB, causes by large and complex molecules, like asphaltene, in high viscous reservoir oil or oil with Non-Newtonian behavior. According to this phenomenon, using solution gas-oil ratio to correlate viscosity equations for high viscous oil is definitely concerned in this work. From this reason, solution gas-oil ratio may not be a perfect variable for correlating a saturated oil viscosity equation.

Plotting reservoir oil viscosity against reservoir oil density, as shown in **Fig. 12**, indicates a strong relationship. An increment in oil density corresponds to an increment in oil viscosity. Noticeably, unlike solution gas-oil ratio, oil density function smoothly applies with the high viscous oil. Based on this relationship, reservoir oil density has a high potential to be the most powerful independent variable for correlating a saturated oil viscosity equation.

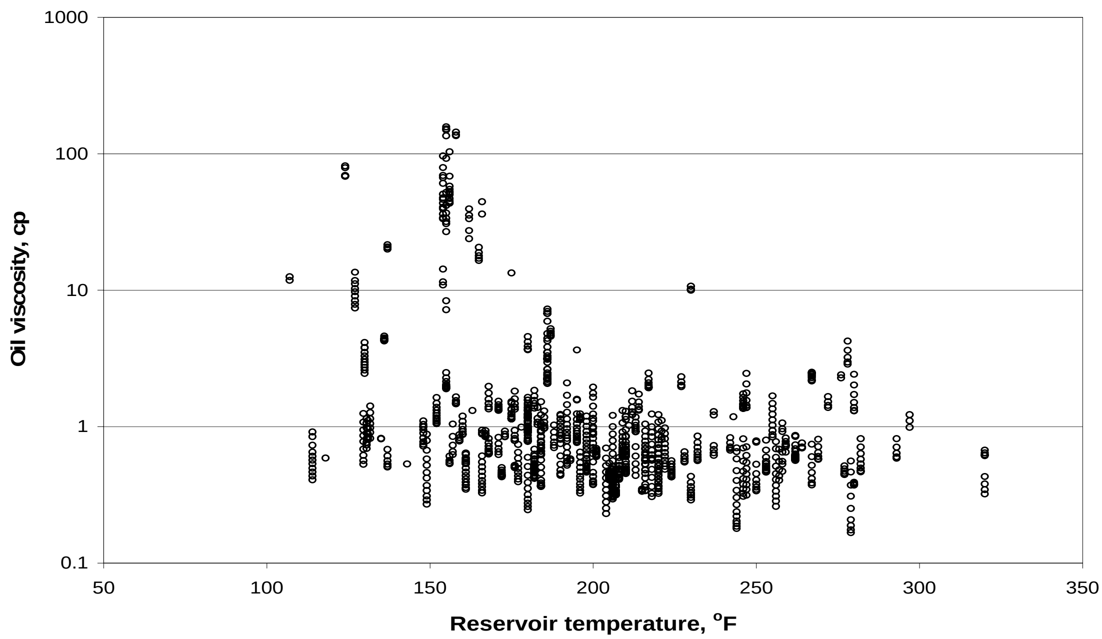

Fig. 9- Saturated oil viscosity data are plotted against reservoir temperature data.

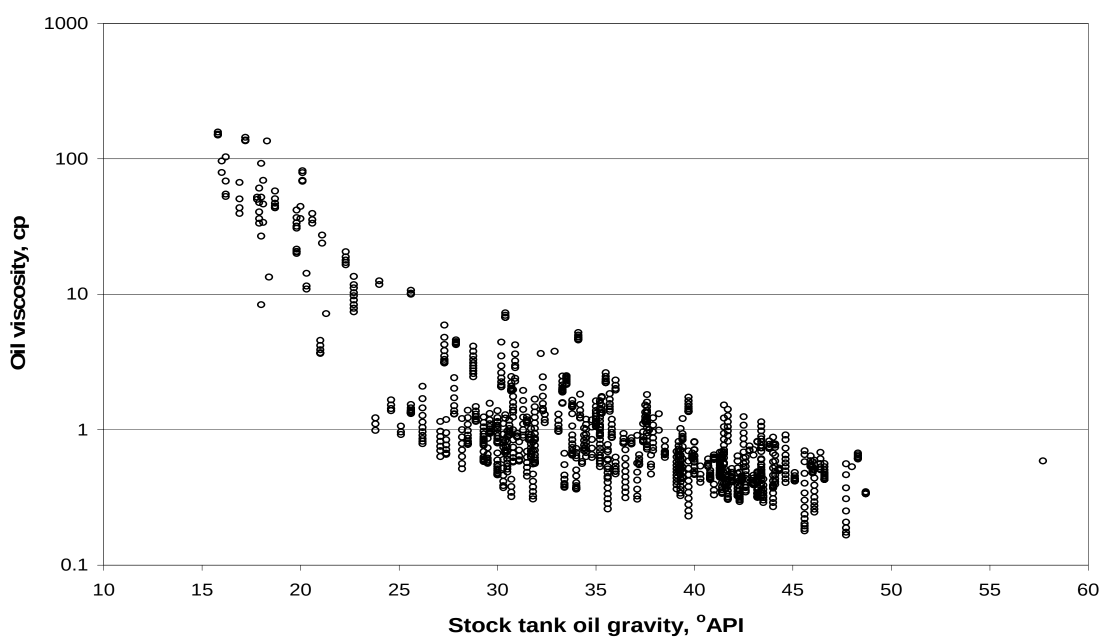

Fig. 10- Saturated oil viscosity data are plotted against stock-tank oil gravity data.

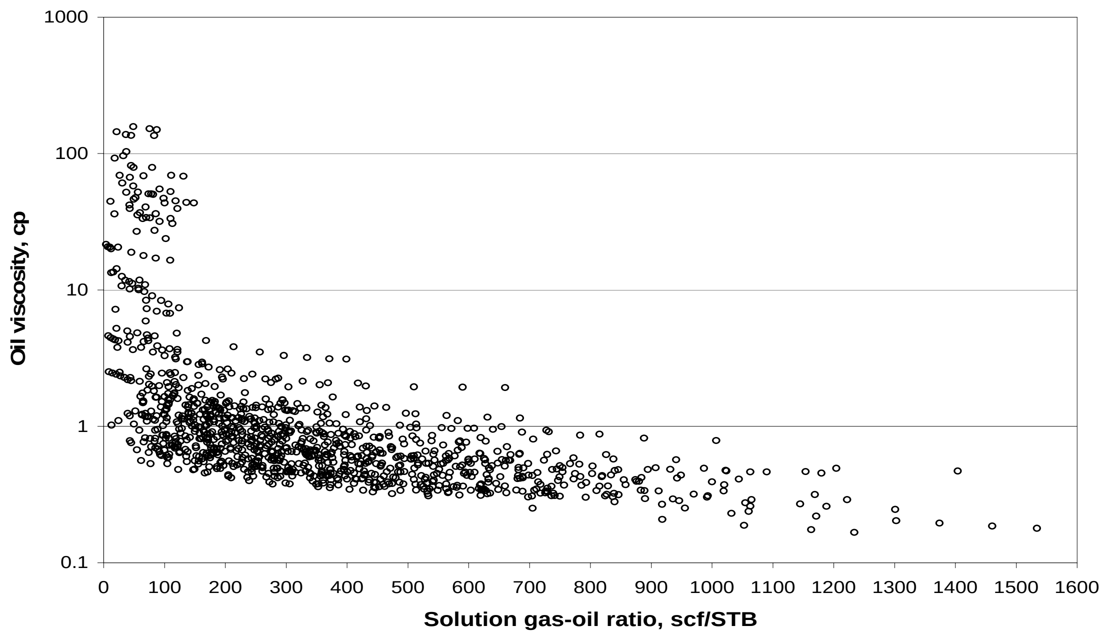

Fig. 11- Saturated oil viscosity data are plotted against solution gas-oil ratio data.

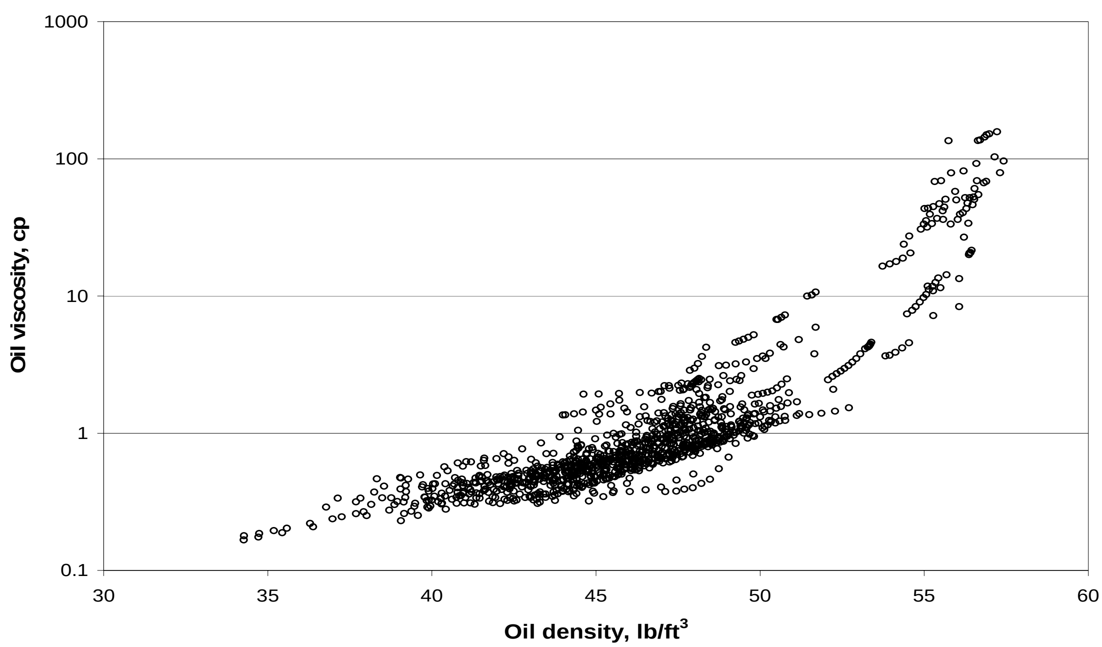

Fig. 12- Saturated oil viscosity data are plotted against reservoir oil density data.

For undersaturated reservoir oil, viscosity data are plotted against reservoir pressure, bubble point pressure, bubble point viscosity, and reservoir oil density, as shown in **Fig. 13** through **Fig. 16**. Based on the results of comparing typical shape section, reservoir oil density has a huge effect on reservoir oil viscosity and qualifies as a potential independent variable for correlating an undersaturated oil viscosity equation. In addition, reservoir pressure, bubble point pressure, and bubble point oil viscosity are also studied in this section because they are the most often used parameters in published correlation equations. These selected reservoir parameters are examined their relationship with viscosity of undersaturated reservoir oil by using the same procedure.

The oil viscosity data are plotted versus reservoir pressure data as shown in **Fig. 13**. The plot shows a tremendous distribution which conceals the confidence of using reservoir pressure to correlate an undersaturated oil viscosity equation. A reservoir oil viscosity indicates a better relationship with a bubble point pressure as shown in **Fig. 14**; but the data distribution in this plot still shows a weak relationship between both parameters. These plots indicate an uncertainty about using a pressure function, which is often used in most publications, in undersaturated oil viscosity correlation equations. To avoid this uncertainty, a pressure function should be replaced with other reservoir functions that show better relationship with reservoir oil viscosity and validate the connection of oil viscosity at the bubble point pressure.

Bubble point oil viscosity is definitely required in an undersaturated oil viscosity correlation equation; because it represents the value of oil viscosity at the exact bubble point pressure. The plot of reservoir oil viscosity versus bubble point viscosity, as shown in **Fig. 15**, indicates the relationship between both parameters.

Plotting viscosity versus density of undersaturated reservoir oil, as shown in **Fig. 16**, indicates a robust relationship. The trend of this plot is quite obvious and corresponds to the behavior of both parameters that provided in a comparing typical shape section. Again, the effect of high viscous fluid is not applied on reservoir oil density. Based on this information, reservoir oil density has a high potential to be used as a powerful independent variable to correlate an undersaturated oil viscosity equation.

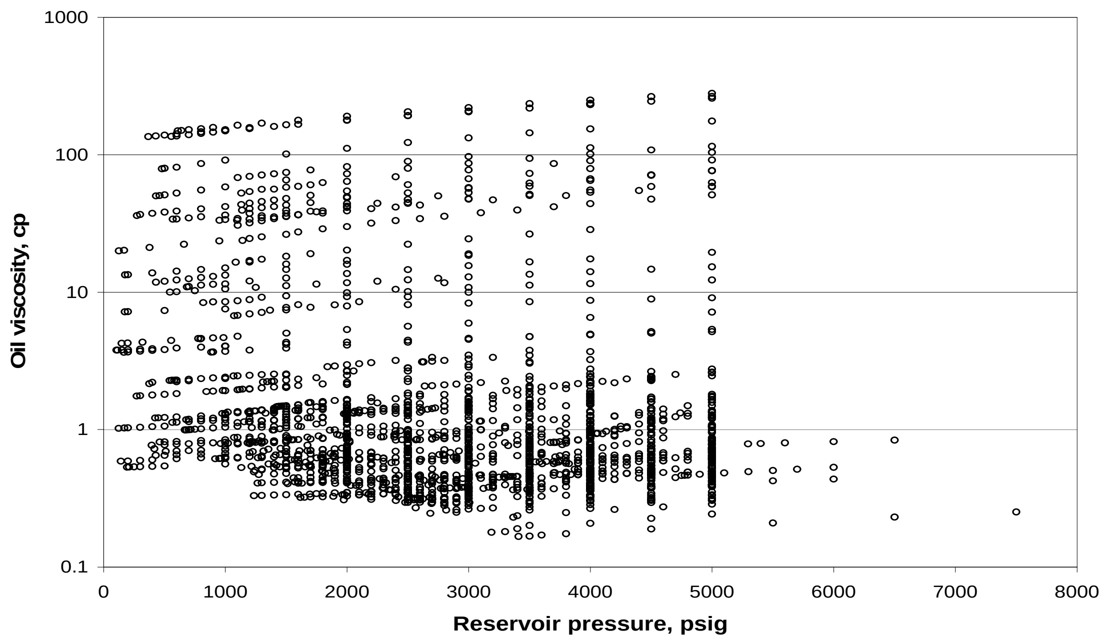

Fig. 13- Undersaturated oil viscosity data are plotted against reservoir pressure data.

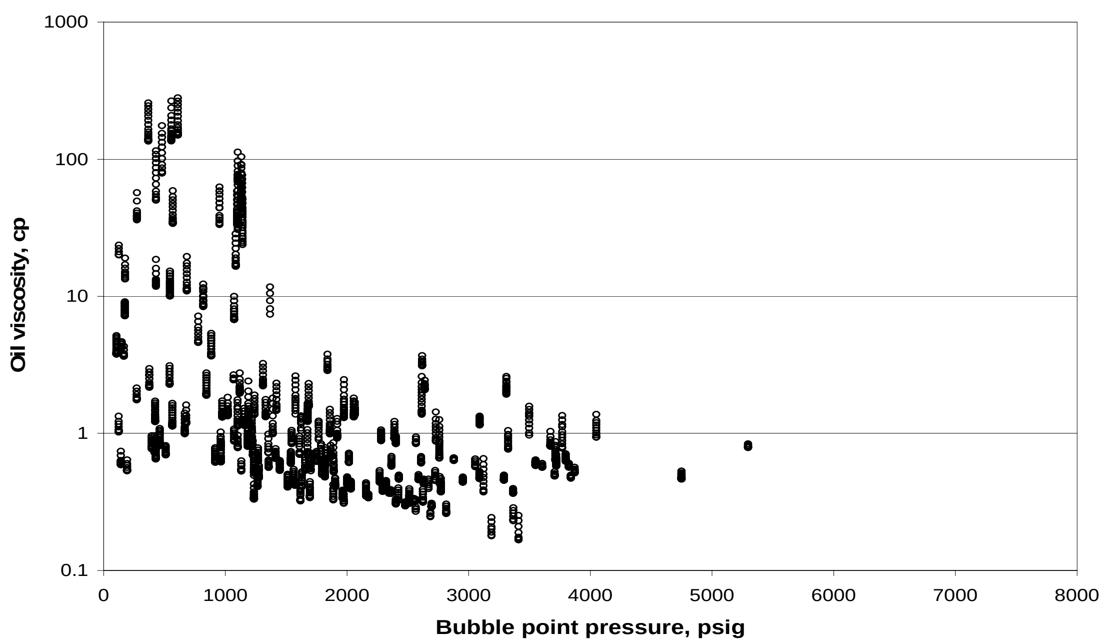

Fig. 14- Undersaturated oil viscosity data are plotted against bubble point pressure data.

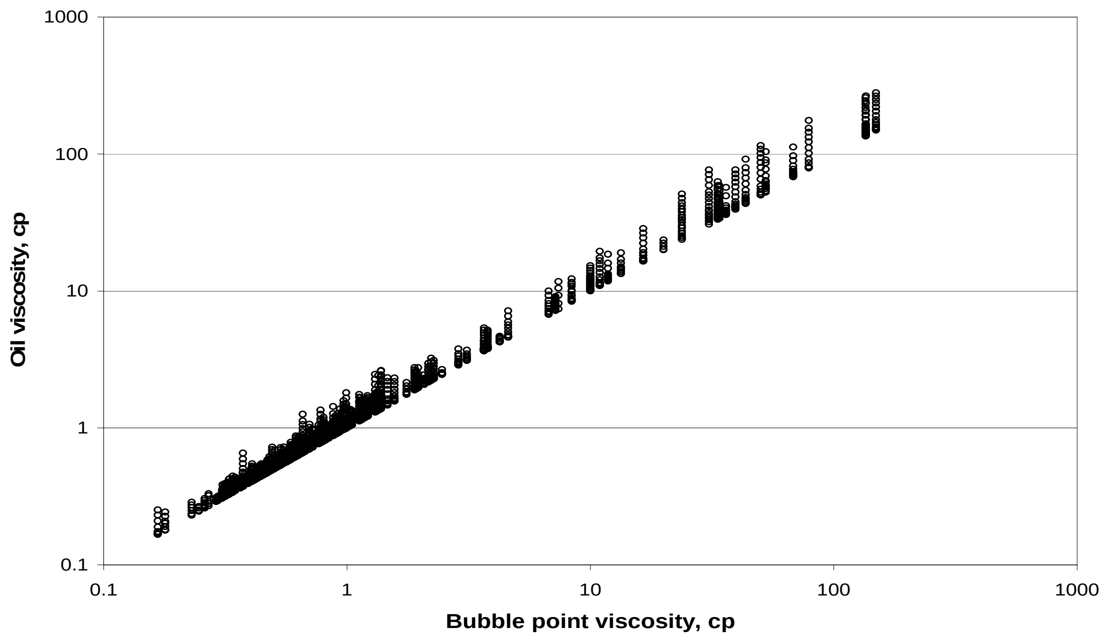

Fig. 15- Undersaturated oil viscosity data are plotted against bubble point viscosity data.

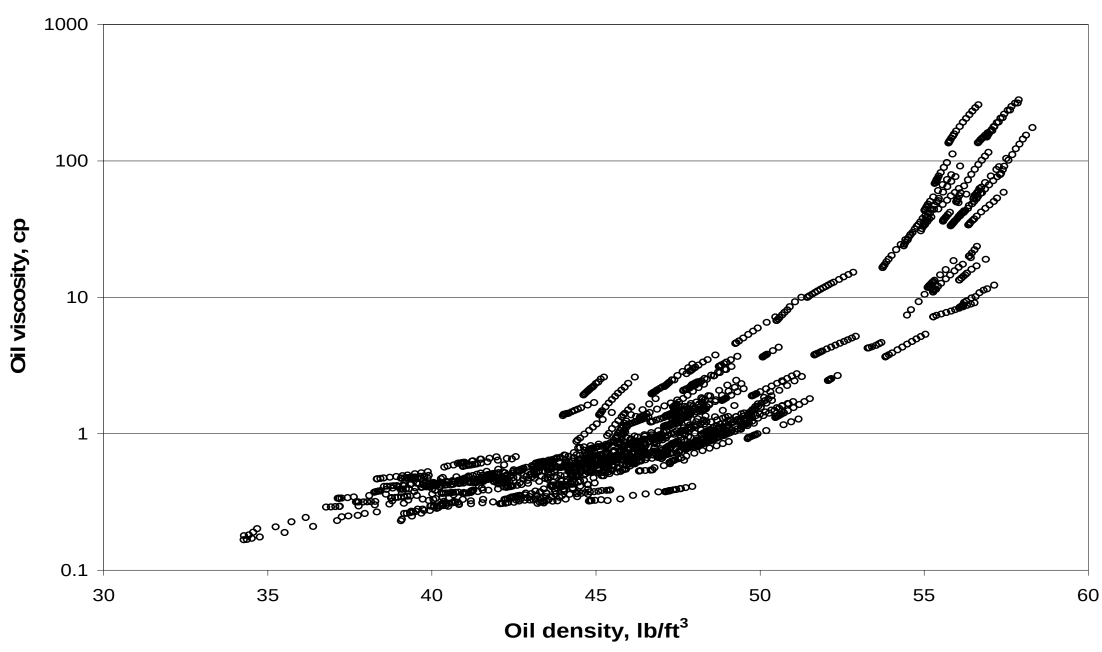

Fig. 16- Undersaturated oil viscosity data are plotted against reservoir oil density data.

Summary

The results of theoretical and empirical studies about the relationship between reservoir oil viscosity and other reservoir parameters can be summarized as follows:

- Reservoir temperature and stock-tank oil gravity, which are considered reservoir constants, have a relatively strong relationship with dead oil viscosity. Reservoir temperature, however, is not a good parameter to correlate saturated and undersaturated oil viscosities, while stock-tank oil gravity can correlate to saturated oil viscosity.
- Solution gas-oil ratio has a relationship with saturated oil viscosity; but, at low solution gas-oil ratio, the high viscous fluid with Non-Newtonian behavior provides a big impact on their relationship.
- Reservoir and bubble point pressures show a weak relationship with undersaturated oil viscosity and these parameters probably are not good for correlating undersaturated oil viscosity equations.
- Bubble point oil viscosity definitely has a strong relationship with reservoir oil viscosity and it is a requisite parameter for verifying the information at the bubble point pressure.
- Reservoir oil density indicates a robust relationship with reservoir oil viscosity and has the possibility of being the most effective parameter for correlating viscosity equations of saturated and undersaturated reservoir oil.

CHAPTER VI

EVALUATING THE EFFICIENCY OF OIL VISCOSITY CORRELATION EQUATIONS FROM THE LITERATURE

This chapter provides overall information about the performance of published oil viscosity correlation equations when they are applied with a database that provides in this study. Saturated and undersaturated oil viscosity correlation equations are tested in terms of statistical error analysis functions. The graphical interpretations of calculated versus laboratory-measured oil viscosities are available in **Appendix A** and **B**.

Statistical and Graphical Error Analysis Methods

Statistical and graphical error analyses are the popular method for evaluating the efficiency of oil viscosity correlation equations. Statistical error analysis method determines the overall accuracy of calculated oil viscosity by using various statistical functions. Average relative error, ARE, and average absolute relative error, AARE, are the statistical error analysis functions that use in this research and they are as follows:

Average Relative Error

$$ARE = \frac{100}{N}\sum_{i=1}^{N}\frac{\mu_{calc}-\mu_{meas}}{\mu_{meas}}, \quad (67)$$

Average Absolute Relative Error

$$AARE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{\mu_{calc}-\mu_{meas}}{\mu_{meas}}\right|, \quad (68)$$

Where μ_{calc} and μ_{meas} are calculated and measured reservoir oil viscosities and N is the total number of data points in the database. Generally, ARE represents the bias of the calculated results; and the errors are more equally distributed in both positive and negative sides if the lower value of ARE is obtained. AARE indicates the absolute deviation of the calculated oil viscosity from the laboratory-measured oil viscosity. The lower the value of AARE, the better the precision of calculated oil viscosity can be achieved from correlation equations.

Graphical error analysis is plotting of calculated versus laboratory-measured oil viscosities on either Cartesian or logarithmic coordinates. Then the perfect correlation line, which is a 45^{o} straight line, is drawn on the figure in order to represent the equalization between calculated and measured oil viscosities. For the high performance correlation equations, the position of plotted data would locate very close to this perfect correlation line.

Results of Performance Tests

The published correlation equations are evaluated their performance in terms of statistical error analysis functions as shown in **Table 7** and **Table 8** for saturated and undersaturated reservoir oil. The order in this table is arranged by the increment of AARE. The results of graphical error analysis for published viscosity correlation equations of saturated and undersaturated reservoir oil are also available in **Appendix A** and **Appendix B**, respectively.

For saturated reservoir oil, the top three published correlation equations are provided by Beggs and Robinson[4], De Ghetto, Paone, and Villa[21], and Dindoruk and Christman[29]. For undersaturated reservoir oil, the top three published equations are provided by Dindoruk and Christman[29], Petrosky and Farshad[23], and Vasquez and Beggs[5]. The best viscosity correlation equations for saturated and undersaturated reservoir oil provide the AARE values of 27.05% and 33.59%, which is considered as high percentage error. The causes of high erroneous results among these published correlation equations probably come from an error in laboratory PVT information and the unreliability in correlation equations.

Table 7- A performance of published viscosity correlation equations for saturated reservoir oil using provided database

Published correlation equations	Predicted saturated oil viscosity	
	ARE, %	AARE, %
Beggs and Robinson (1975)	-6.33	27.05
De Ghetto, Paone, and Villa (1994)	1.97	28.51
Dindoruk and Christman (2001)	-10.06	29.24
McCain* (1990)	1.82	29.58
Almehaideb (1997)	-5.56	29.61
Petrosky and Farshad (1995)	1.04	29.84
Standing (1977)	-4.69	31.22
Elsharkawy and Gharbi (2001)	-7.43	31.63
Al-Khafaji, Abdul-Majeed, and Hassoon (1987)	-10.58	33.10
Kartoatmodjo and Schmidt (1991)	-9.86	33.63
Bergman (1992)	10.74	33.82
Hanafy *et al.* (1997)	9.70	34.53
Abu-Khamsin and Al-Marhoun (1991)	17.77	38.92
Elsharkawy and Alikhan (1999)	19.86	38.94
Aziz, Govier, and Fogarasi (1972)	24.52	44.25
Khan *et al.* (1987)	40.94	61.69
Labedi (1992)	53.23	79.48

*Author used the combination of Ng and Egbogah[8] correlation and Beggs and Robinson[4] correlation

Table 8- A performance of published viscosity correlation equations for undersaturated reservoir oil using provided database

Published correlation equations	Predicted undersaturated oil viscosity	
	ARE, %	AARE, %
Dindoruk and Christman (2001)	-18.26	33.59
Petrosky and Farshad (1995)	-9.83	33.99
Vasquez and Beggs (1980)	-14.13	34.88
McCain* (1990)	-5.29	35.26
De Ghetto, Paone, and Villa (1994)	-11.52	35.87
Standing (1977)	-17.31	35.87
Hanafy *et al.* (1997)	-6.63	36.26
Elsharkawy and Alikhan (1999)	2.49	36.60
Almehaideb (1997)	-10.45	36.79
Abu-Khamsin and Al-Marhoun (1991)	2.15	38.90
Kartoatmodjo and Schmidt (1991)	-23.98	39.85
Elsharkwy and Gharbi (2001)	-11.80	40.09
Khan *et al.* (1987)	-3.22	40.77
Al-Khafaji, Abdul-Majeed, and Hassoon (1987)	43.39	74.39
Labedi (1992)	49.20	83.44

*Author used the combination of Ng and Egbogah[8] correlation, Beggs and Robinson[4] correlation, and Vasquez and Beggs[5] correlation.

Very interesting, the results of graphical error analysis for both saturated and undersaturated reservoir oil indicate that most published correlation equations can not perform effectively at high viscosity ranges. These correlation equations were originally developed by assuming that reservoir oil behaves like a Newtonian fluid, which is not always true when high viscous oil is in the system. Generally reservoir fluid having oil viscosity less than 10 cp is considered as a Newtonian fluid; otherwise they could be a Non-Newtonian fluid[21]. This Non-Newtonian behavior affects the efficiency of oil viscometer in laboratory and causes the deviation in laboratory-measured oil viscosity data. Furthermore, even on the same fluid sample, differences up to 10% between two measurements by two different equipments are normal at the high viscosity ranges[21]. Most correlation developers, however, may not concern about this issue and develop their oil viscosity correlation equations by using the erroneous information. Therefore, some hidden errors can degrade the efficiency and the reliability of their correlation equations.

High viscous reservoir oil and Non-Newtonian behavior are considered as hidden factors that cause errors in routine laboratory measurement of oil viscosity. These errors provide an effect on a deficiency for predicting reservoir oil viscosity in most published correlation equations, which represents the high percentage values of AARE.

Summary

From the statistical analysis results the following can be summarized:

- Saturated and undersaturated oil viscosity correlation equations proposed by Beggs and Robinson[4] and Petrosky and Farshad[23] give the best overall statistical error analysis results. Advantages of these equations are requiring basic input parameters, using a simple calculation method, and providing a fair accuracy.
- Correlation equations proposed by Dindoruk and Christman[29] and De Ghetto, Paone, and Villa[21] predict reservoir oil viscosity with some accuracy but they are not simply to use and require several input parameters.
- The Abu-Khamsin and Al-Marhoun[18] and the Hanafy *et al.*[25] correlation equations can not provide the precise outcomes; because they use only oil density at the bubble point pressure, instead of oil density at reservoir conditions, to correlate their reservoir oil viscosity equations.
- The Khan *et al*[11] and the Labedi[19] correlation equations predict reservoir oil viscosity with the lowest accuracy. The results confirm the unprofitable use of a bubble point oil viscosity correlation equation in their publications.
- Errors in routine laboratory measurement of oil viscosity provide a direct effect on the quality of oil viscosity and cause an indirect effect on the performance of published correlation equations.

CHAPTER VII

CORRELATING VISCOSITY EQUATIONS FOR SATURATED RESERVOIR OIL

All assumptions and methodologies for correlating viscosity of saturated reservoir oil are presented in this chapter. The main topics are as follows:

- A Statistical Method for Correlating Oil Viscosity Equations
- An Alternating Conditional Expectations Technique
- A Data Reconciliation Technique
- A Forward Stepwise Procedure for Correlating Oil Viscosity Equations
- Errors in Routine Laboratory Measurement of Oil Viscosity

A Statistical Method for Correlating Oil Viscosity Equations

In statistical methods, two main subdivisions of regression analysis are parametric and nonparametric approach. Parametric approach is often used if the form of functional relationship between the dependent and independent variables is priori known or fully described by a finite set of parameters. A prescribed parametric model might be too limited or too low-dimensional to fit unexpected features[36]; and, sometimes, it does not really correspond to the actual data, which is the main problem of parametric approach. Usually the ultimate goal of parametric regression is to estimate the coefficients of the intrinsic models. On the other hand, nonparametric approach does not force the data into a fixed parameterization and not require a priori knowledge about the true functional form and the error distribution of the observed data. Therefore, the primary purpose of nonparametric regression is to explore the underlying function of the actual data between the dependent and independent variables and to offer a flexible tool for analyzing an unknown relationship[36].

According to the plots of reservoir oil viscosity against other laboratory-measured parameters as shown in Chapter V, most relationships between the dependent and independent variables are not applied with parametric regression. Therefore, an effective nonparametric regression technique is the best solution for correlating reservoir oil viscosity equations in this research.

An Alternating Conditional Expectations Technique

In 1985, Breiman and Friedman[37] developed an iterative optimal transformation technique called alternating conditional expectations, ACE. The method of ACE corroborates the minimum error relationship and establishes the maximum correlation between the transformed dependent variable and the sum of transformed independent variables. ACE was applied successfully with petroleum engineering researches in the past decade. Xue *et al.*[38] (1997) used ACE technique to fit permeability versus porosity data. McCain *et al.*[39] (1998) correlated a bubble point pressure equation for reservoir oil. Valkó and McCain[40] (2003) developed three correlation equations for bubble point pressure, solution gas-oil ratios, and surface gas specific gravities.

The first step of ACE algorithm is to find an optimal transformation of the dependent and independent variables. An iterative procedure to minimize the regression error between the transformed dependent variable and the sum of transformed independent variables is performed in order to obtain the optimal transformations. Individual transformations of the independent variables, x_1, x_2, ...x_n, and the dependent variable, y, are provided as follows:

$$z_1 = f_1(x_1),\, z_2 = f_2(x_2),\, \ldots\, z_n = f_n(x_n) \quad and \quad z_0 = f_0(y), \qquad (69)$$

where z_1, z_2,…z_n are transformed independent variables; $f_1(\cdot)$, $f_2(\cdot)$,…$f_n(\cdot)$ are optimal transformation functions for independent variables; z_0 is a transformed dependent variable; and $f_0(\cdot)$ is an optimal transformation function for dependent variable.

Optimal transformation functions from ACE technique do not necessarily represent in terms of certain algebraic forms, but rather as point-wise expressions. In addition, shape and range of the transformed variables provide information about the influence of independent variables on the dependent variable; for example see Breiman and Friedman[37].

In practice, most correlations deal with a finite data set, which are presumably sampled from random variables. Therefore, the dependent and independent variables from this data set can have a random error. To eliminate the outliers and smooth the transformation functions, the ACE algorithm must be applied with an additional restriction, which is some sorts of smoothing techniques[37], on the individual transformations. Furthermore, the smoothness for the transformations provides a substantial contribution for deriving a functional form of these transformations in the next step.

The method of ACE is designed to achieve the maximum correlation between the transformed dependent variable and the sum of transformed independent variables in the transformed space, which represents as a 45^{o} straight line on the plot. Therefore, the next step is to calculate the transformed dependent variable as a function of the summation of transformed independent variables as follows:

$$z_0 = \sum_{n=1}^{m} z_n \text{ ,} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (70)$$

The final step of ACE method is to apply the inverse transformation, $f_0^{-1}(\cdot)$, for the transformed dependent variable to determine the predicted dependent variable, y^{pre}, as follows:

$$y^{pre} = f_0^{-1}(z_0), \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (71)$$

The results of the ACE algorithm are generally given in form of the transformed dependent and independent variables; and, sometimes, the results are shown on the plot of transformed versus original variables. However, no functional forms for these transformations are provided with the outcomes. Therefore, curve fitting methods are required to generate functional forms of these transformed variables. The shape of the individual transformation from ACE algorithm is relatively smooth and simple; and quadratic polynomials are rather good enough to represent an algebraic form of the individual transformation.

In this research, the graphical alternating conditional expectation, GRACE, software[38] is used to develop reservoir oil viscosity correlation equations. The program consists of two sections. For the first section, the program performs ACE algorithm to obtain the optimal transformations for the dependent and independent variables in the format of point-by-point plot and table. For the second section, the EXCEL macro is used to determine the functional form of the optimal transformations by generating the plots and performing polynomial curve fitting method. Another interesting option in GRACE software is data reconciliation technique, which describes the quality of the data used to derive the proposed oil viscosity correlation equations.

A Data Reconciliation Technique

Data reconciliation is a statistical technique created for improving the accuracy of process data by detecting random errors and adjusting the measured values to satisfy the provided process constraints. During the past 35 years, this technique has been developed and designed especially for chemical or petrochemical industries. Nowadays, it is widely used in refineries, petrochemical plants, mineral processing industries, etc., to achieve more economization and better plant operations[41]. However, this technique is rarely seen in petroleum engineering; and only few publications apply data reconciliation technique for investigating the quality of measured observations; for example see Xue *et al.*[38] and Valkó and McCain[40].

To clarify the quality of all laboratory-measured parameters used for correlating oil viscosity equations, data reconciliation technique is totally needed in this research. Fortunately, GRACE software has an option to reconcile all laboratory-measured data in order to analyze the random error in laboratory procedures. The reconciled values are obtained by simultaneously adjusting the observed dependent and independent variables to approach the constraint, which indicates that all reconciled data points must thoroughly fit the 45^o straight line in a transformed space, whereas minimizing the overall change in each observed value[38].

The relationship between reconciled and observed values is presented in terms of statistical analysis functions, average relative adjustment, ARA, and average absolute relative adjustment, AARA. The term ARA indicates a bias of the laboratory procedures for measuring the observed parameters. For example, the extremely low value of ARA indicates a random error distribution of laboratory-measured data or no bias. The term AARA presents the quality and the average precision of individual variable in the database. The lower value of AARA, the better precision of observed parameters is obtained from the laboratory procedures.

A Forward Stepwise Procedure for Correlating Oil Viscosity Equations

A forward stepwise procedure is applied in this research to correlate saturated oil viscosity model. The dependent variable, reservoir oil viscosity, is correlated with 8 independent variables, which are stock-tank oil gravity, reservoir temperature, solution gas-oil ratio, separator gas specific gravity, reservoir pressure, bubble point pressure, bubble point solution gas oil ratio, and reservoir oil density. For the first step, the 8 bivariate cases involving the dependent variable, y, with each of independent variables in the first stage, $x_{n,1}$ ($1 \leq n \leq 8$), are tested to find out which case maximizes a linear correlation R^2 of the transformed variables, z_0 and $z_{n,1}$. Then, an independent variable in the first stage, $x_{n,1}$, will be kept in the model. The next step (over the remaining 7 independent variables) includes 7 trivariate cases involving the dependent variable, y, and an independent variable in the first stage, $x_{n,1}$, with each of independent variables in the second stage, $x_{n,2}$ ($1 \le n \le 7$). Then independent variables in the second stage that maximizes a linear correlation R^2 between the transformed dependent variable, z_0, and the summation of transformed independent variables, $\Sigma(z_{n,1}, z_{n,2})$ will be kept in the model. This forward selection process is continued until the best independent variable of the next step improves a linear correlation R^2 of the previous step by less than 1 percentage[37]. A linear correlation R^2 is calculated as follows:

$$R^2 = \left(\frac{\sum_{i=1}^{N} \left(z_{0,i} - \bar{z}_{0,i}\right)\left(z_{n,i}^* - \bar{z}_{n,i}^*\right)}{\sqrt{\sum_{i=1}^{N} \left(z_{0,i} - \bar{z}_{0,i}\right)^2 \sum_{i=1}^{N} \left(z_{n,i}^* - \bar{z}_{n,i}^*\right)^2}} \right)^2 , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(72)}$$

where N is total number of data points from the database and z_n^* is summation of transformed independent variables as follows:

$$z_n^* = \sum_{j=1}^{k} z_{n,j} , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(73)}$$

where k is total number of independent variables used for correlating oil viscosity equation.

By using an input option from GRACE, the user can select variables in either the original form or the natural logarithmic form for positive data. In this research, both input forms are tested to determine the best correlation equations for saturated oil viscosity. For the first round of the forward stepwise procedure, the correlation R^2 values of bivariate cases, which represents the relationship between the transformed reservoir oil viscosity and each of transformed field-measured parameters, are provided in **Table 9**.

Table 9- Finding optimal correlation R^2 of transformed variables for bivariate cases (saturated oil viscosity correlation)		
Dependent variable	**First stage independent variable**	**Correlation R^2**
$\ln \mu_o$	γ_g	0.14
	$\ln \gamma_g$	0.14
	p	0.24
	$\ln p$	0.24
	T	0.27
	$\ln T$	0.27
	p_b	0.37
	$\ln p_b$	0.38
	R_S	0.59
	$\ln R_S$	0.58
	R_{Sb}	0.61
	$\ln R_{Sb}$	0.58
	API	0.90
	$\ln API$	0.90
	ρ_o	0.90
	$\ln \rho_o$	0.90

Based on the results of correlation R^2 in **Table 9**, reservoir oil viscosity indicates a robust relationship with reservoir oil density and stock-tank oil gravity by representing the correlation R^2 values up to 0.90. Solution gas-oil ratio provides a fair relationship with reservoir oil viscosity as shown by correlation R^2 value of 0.58. The lower correlation R^2 values are found from bubble point pressure, reservoir temperature, reservoir pressure, and separator gas specific gravity, respectively. Very interesting, these results definitely correspond to the summary given in Chapter V.

The study in Chapter V confirms that oil density has a strong relationship with oil viscosity; and, noticeably, stock-tank oil gravity can be converted to oil density at the standard condition or stock-tank oil density. From this reason, using stock-tank oil density instead of stock-tank oil gravity to correlate a saturated oil viscosity equation reveals the actual relationship between viscosity and density functions and possibly improves the performance of correlation equations in this research. This concept is unique and has never been done by any published correlation equations in petroleum industry. The equation that converts stock-tank oil gravity to stock-tank oil density is provided as follows:

$$\rho_{sto} = \left(\frac{141.5}{131.5 + API} \right) \rho_w , \ldots\ldots (74)$$

where ρ_w is water density at standard condition and equals to 62.368 lb/ft^3.

Reservoir oil and stock-tank oil densities have very close correlation R^2 values (within 0.005 decimal); but one of them will be chosen as an independent variable in the first stage. The standard deviation, SD, is performed to determine the distribution of predicted oil viscosity derived from reservoir oil density and stock-tank oil density. Theoretically, the lower SD value corresponds to a better estimation of reservoir oil viscosity. From this reason, the parameter that minimizes the SD value will be used as an independent variable in the first stage in this work. The SD is calculated as follows:

$$SD = \sqrt{\frac{\sum_{i=1}^{N} \left(r_i - \bar{r} \right)^2}{\left(N - 1 \right)}} , \ldots\ldots (75)$$

where r is a residual, which is the difference between laboratory-measured and predicted oil viscosity, and can be calculated as follows:

$$r = y - y^{pre} , \ldots\ldots (76)$$

The results show that the value of SD for predicted oil viscosity derived from reservoir oil density is smaller than that for predicted oil viscosity derived from stock-tank oil density. Furthermore, the graphical interpretations are also provided by GRACE software to support these results. The plot of predicted oil viscosity as a function of oil density versus laboratory-measured oil viscosity indicates a lower distribution around a 45^o straight line, as shown in **Fig. 17**, which represents a better prediction of reservoir oil viscosity. On the other hand, a huge dispersion on the plot of predicted oil viscosity as a function of stock-tank oil density versus laboratory-measured oil viscosity, as shown in **Fig. 18**, indicates a lower efficiency of this parameter.

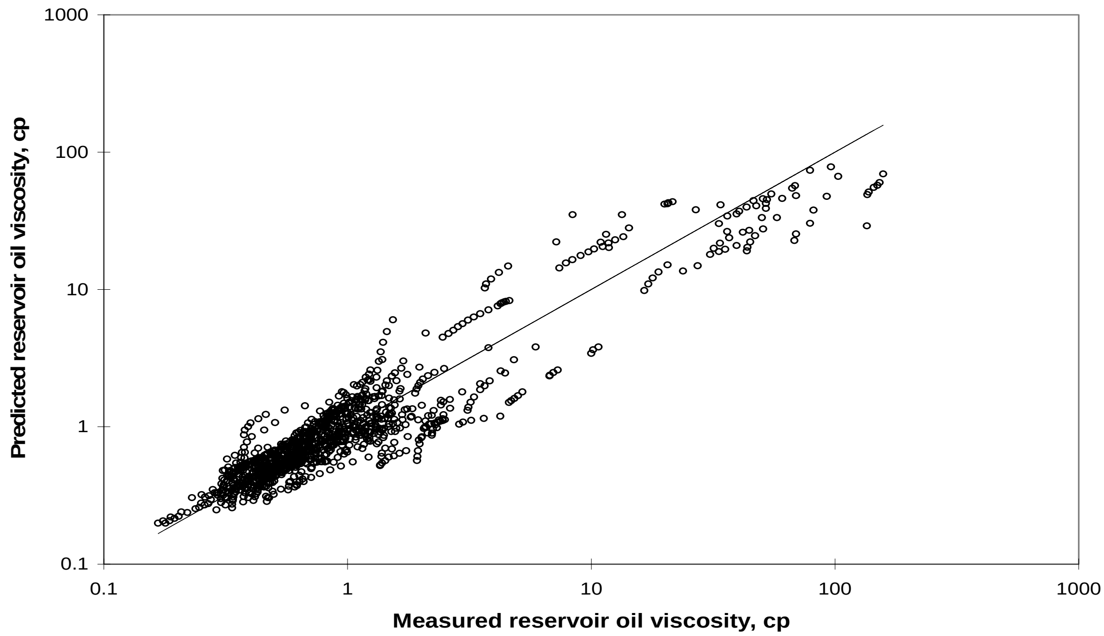

Fig. 17- Comparison of predicted oil viscosity as a function of reservoir oil density and laboratory-measured oil viscosity provides the SD value of 0.40.

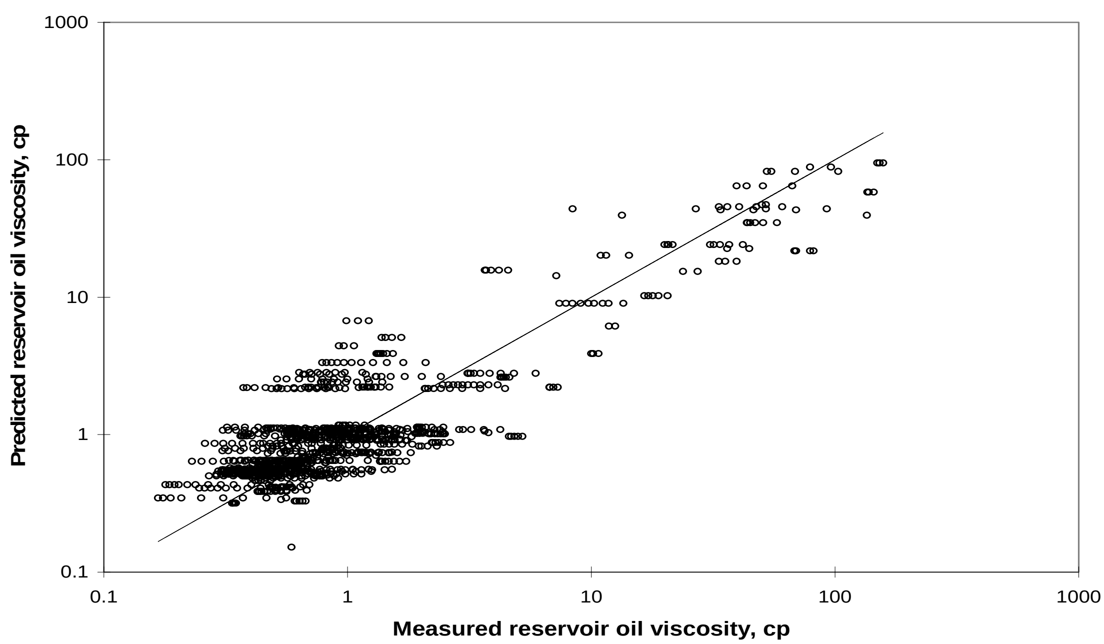

Fig. 18- Comparison of predicted oil viscosity as a function of stock-tank oil density and laboratory-measured oil viscosity provides the SD value of 0.57.

Based on these results, reservoir oil density is a primary contributor for correlating the accurate saturated oil viscosity equation and is used as an independent variable in the first stage for a bivariate case. However, stock-tank oil density provides a high potential to be used as an independent variable in the second stage for improving the correctness of a correlation equation in the next step.

The next step of forward stepwise procedure is searching for an independent variable in the second stage that can increase a correlation R^2 by more than 1%. The current correlation equation includes the natural logarithmic form of reservoir oil viscosity as the dependent variable and reservoir oil density as an independent variable in the first stage. For trivariate cases, the correlation R^2 results and the percentage of improvement are provided in **Table 10**. The results show that adding stock-tank oil density into the oil viscosity correlation equation can maximize the correlation R^2 value and can improve the value up to 1.52%. Therefore, an independent variable in the second stage for correlating a saturated oil viscosity equation is a stock-tank oil density. However, this miniscule improvement of the correlation R^2 possibly indicates the small influence of adding an independent variable in the second stage in the proposed saturated oil viscosity correlation equation. Therefore, a careful inspection is very necessary to avoid the use of redundant independent variables in the proposed equation.

Table 10- Finding optimal correlation R^2 of transformed variables for trivariate cases (saturated oil viscosity correlation)

Dependent variable	First stage independent variable	Second stage independent variable	Correlation R^2	Improvement, %
$\ln \mu_o$	ρ_o	γ_g	0.90	0.86
		$\ln \gamma_g$	0.90	0.83
		p	0.90	0.14
		$\ln p$	0.90	0.17
		T	0.91	1.04
		$\ln T$	0.91	1.05
		p_b	0.90	0.49
		$\ln p_b$	0.90	0.66
		R_S	0.90	-0.02
		$\ln R_S$	0.90	0.21
		R_{Sb}	0.90	0.69
		$\ln R_{Sb}$	0.90	0.58
		ρ_{sto}	**0.91**	**1.51**
		$\ln \rho_{sto}$	0.91	1.44

For an independent variable in the third stage, the results in **Table C-1** show that the remaining independent variables can not improve correlation R^2 values by more than 1%. Some independent variables even decrease a correlation R^2 value, which indicates a low degree of relationship between the dependent and independent variables. Therefore, the forward stepwise procedure is terminated at the trivariate case; and the proposed viscosity correlation equation for saturated reservoir oil is provided in terms of reservoir oil density, as a main contributor, and stock-tank oil density, as a secondary contributor.

In this study, two saturated oil viscosity correlation equations are proposed to compare the performance. The first oil viscosity equation is correlated as a function of reservoir oil density only. Then a stock-tank oil density is added in the first equation to examine the improvement. Either of these correlation equations that precisely predict saturated oil viscosity will be selected as the proposed saturated oil viscosity correlation equation in this research.

For the first proposed model (bivariate case), GRACE software provides graphical interpretation for transformed reservoir oil density, ρ_{o_tr}, and the transformed reservoir oil viscosity, $\ln \mu_{o\_tr}$, as shown in **Fig. 19** and **Fig. 20**. For oil density less than 50 lb/ft^3, reservoir oil viscosity increases gradually with increasing oil density; whereas the oil viscosity rapidly increases at the larger oil density as shown in **Fig. 19**. This significant increment causes by the Non-Newtonian flow behavior of high viscous reservoir oil. The almost linear shape of the transformed viscosity in **Fig. 20** indicates that the natural logarithmic transformation is appropriate for this variable.

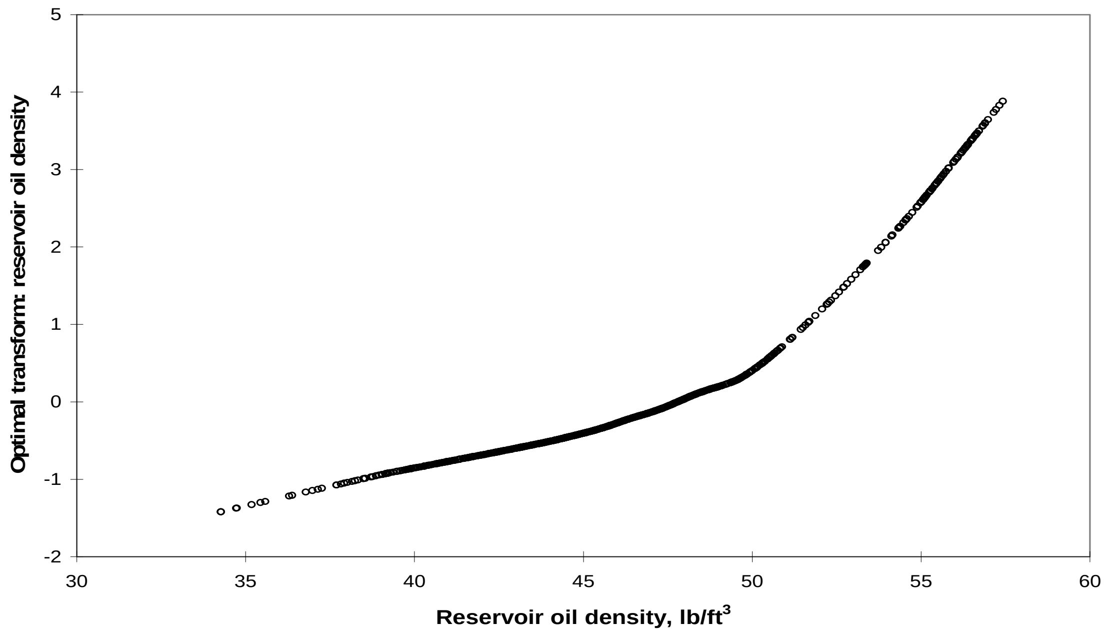

Fig. 19- GRACE optimal transformation of reservoir oil density for saturated reservoir oil (bivariate case for μ_o and ρ_o).

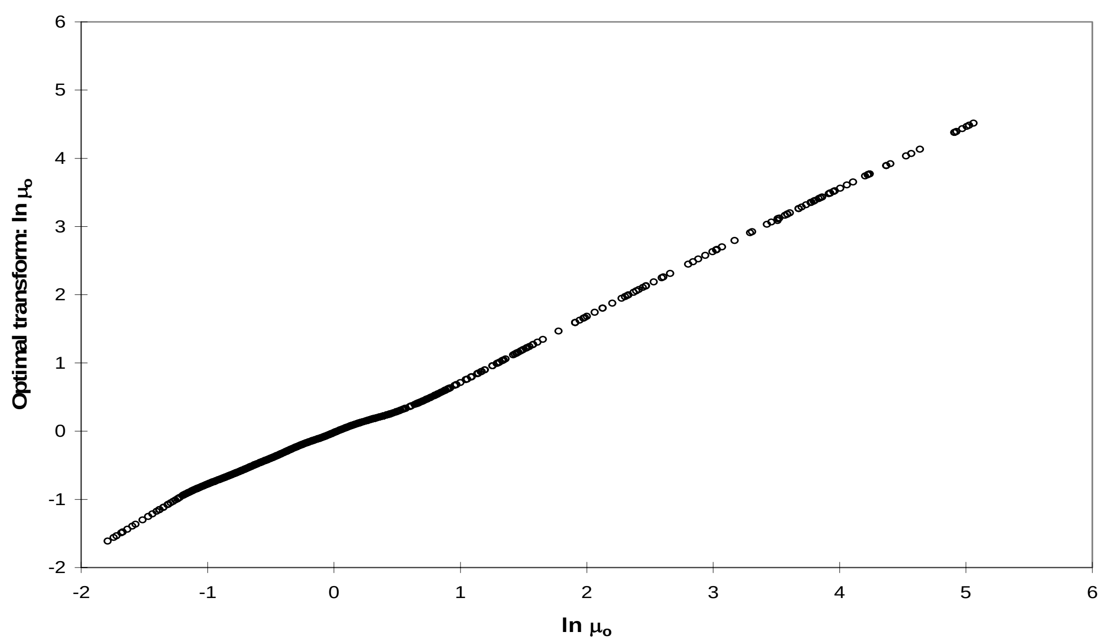

Fig. 20- GRACE optimal transformation of reservoir oil viscosity for saturated reservoir oil (bivariate case for μ_o and ρ_o).

Then the curve fitting procedure using low order polynomials is performed on the transformed reservoir oil density and the inverse transformation of the reservoir oil viscosity to get their functional forms. The finalize equations represents the third order polynomial models as follows:

Functional form of the transformed reservoir oil density

$$\rho_{o\_tr} = 8.0898 \cdot 10^{-4} \cdot \rho_o^3 - 0.10157 \cdot \rho_o^2 + 4.3219 \cdot \rho_o - 63 \text{,.................... (77)}$$

Functional form of the inverse transformation of the reservoir oil viscosity

$$\mu_o = \exp(0.0508 \cdot \rho_{o\_tr}^3 - 0.0487 \cdot \rho_{o\_tr}^2 + 1.0463 \cdot \rho_{o\_tr} + 0.02129) \text{,.......... (78)}$$

where ρ_o is reservoir oil density in lb/cu ft and μ_o is reservoir oil viscosity in cp.

The values of ARE and AARE calculated from the proposed equations are -0.96% and 25.15%, respectively. Based on the result of ARE, a small bias is found from the proposed correlation equations, which indicates an equal distribution around a 45^o straight line. The value of AARE from the proposed correlation equation is too high and is not satisfactory; but it is relatively better than the results from other published correlation equations that are provided in Chapter VI. The high AARE values from the proposed and published saturated oil viscosity correlation equations can infer that the procedure for creating oil viscosity correlation equations is not the main reason of these high percentage errors; but the actual source of errors comes from the low quality of oil viscosity in the database. The graphical interpretations of calculated and laboratory-measured saturated oil viscosity are shown in **Fig. 21** and **Fig. 22** for Cartesian and logarithmic coordinates, respectively.

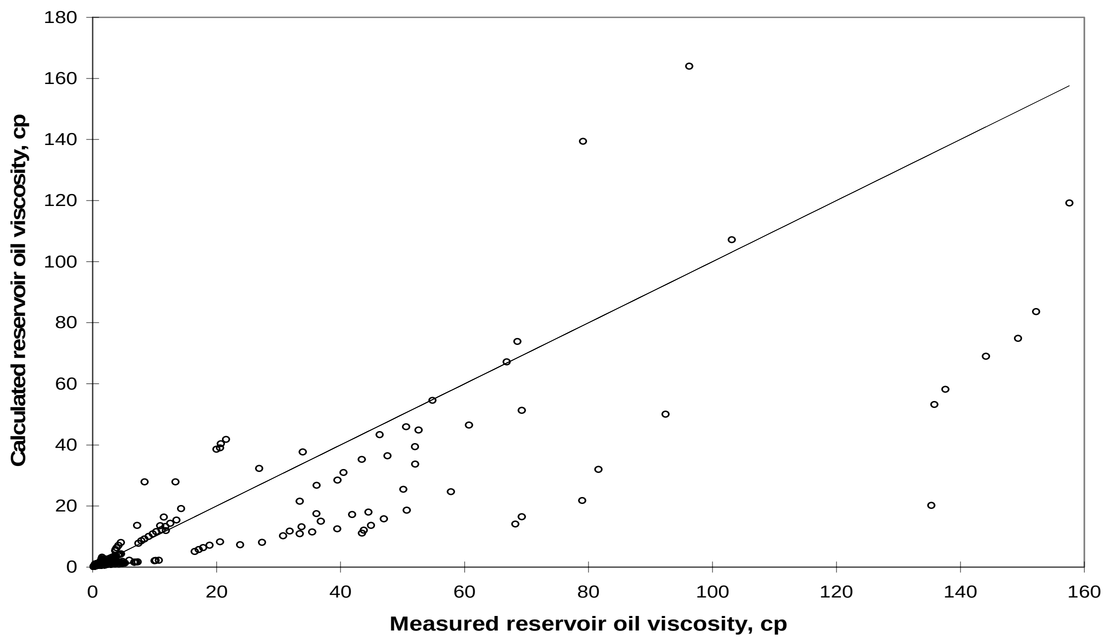

Fig. 21- Calculated and measured saturated oil viscosities are compared on Cartesian coordinates for bivariate case (μ_o and ρ_o).

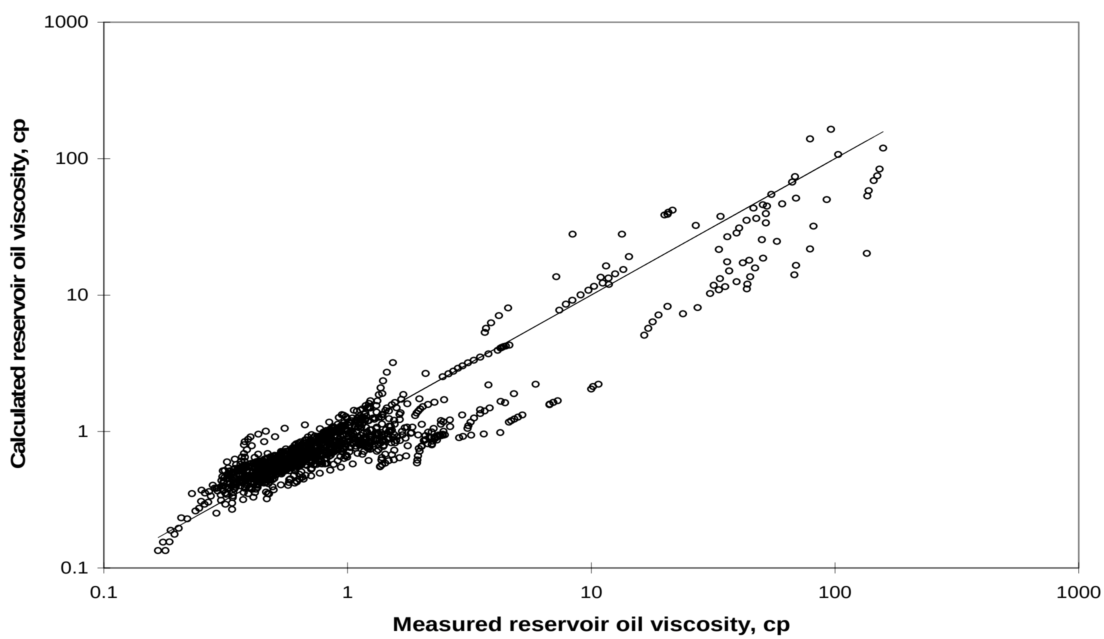

Fig. 22- Calculated and measured saturated oil viscosities are compared on logarithmic coordinates for bivariate case (μ_o and ρ_o).

For the next proposed model (trivariate case), reservoir oil viscosity is correlated with reservoir oil density and stock-tank oil density. The graphical interpretations of optimal transformations of reservoir oil density, ρ_{o_tr}, stock-tank oil density, ρ_{sto_tr}, and oil viscosity, ln μ_{o_tr}, provided by GRACE software are shown in **Fig. 23**, **Fig. 24**, and **Fig. 25**, respectively. The shapes of transformed reservoir oil density and transformed reservoir oil viscosity are similar to **Fig. 19** and **Fig. 20** for bivariate case, which indicate the similar behavior. Based on **Fig. 24**, the majority of stock-tank oil densities, at the values less than 55 lb/ft^3, scarcely relate with reservoir oil viscosity as shown by a rough horizontal line at the first section. Then the influence of high viscous reservoir fluid substantially enhances reservoir oil viscosity at higher stock-tank oil density value as shown by a sharp increment of a transformed stock-tank oil density. From this reason, stock-tank oil density may not provide an outstanding improvement for a saturated oil viscosity correlation equation.

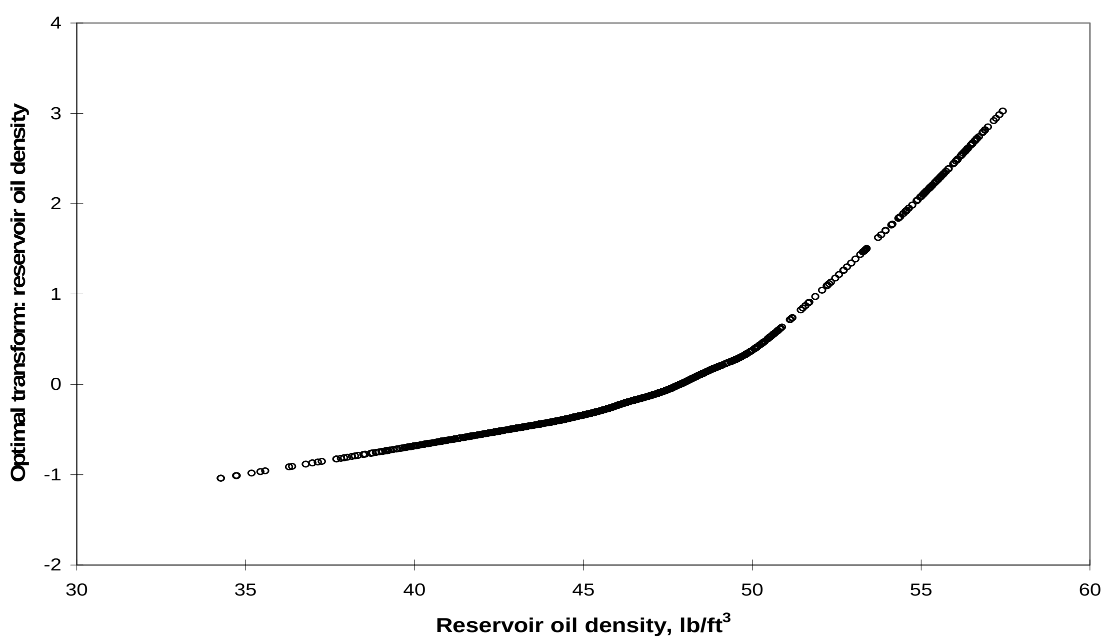

Fig. 23- GRACE optimal transformation of reservoir oil density for saturated reservoir oil (trivariate case for μ_o, ρ_o, and ρ_{sto}).

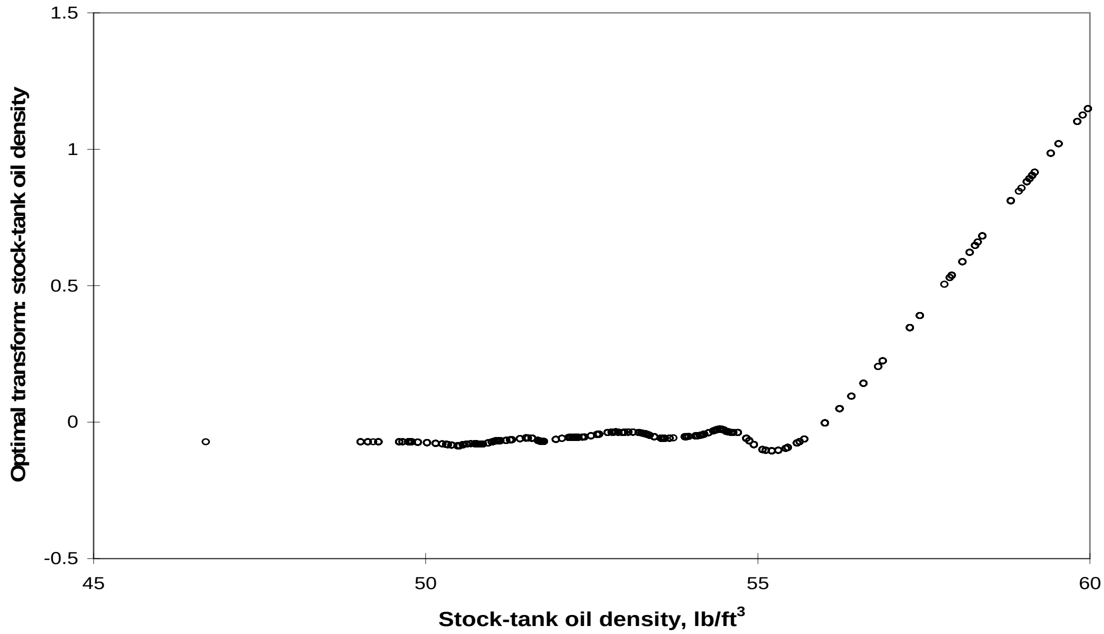

Fig. 24- GRACE optimal transformation of stock-tank oil density for saturated reservoir oil (trivariate case for μ_o, ρ_o, and ρ_{sto}).

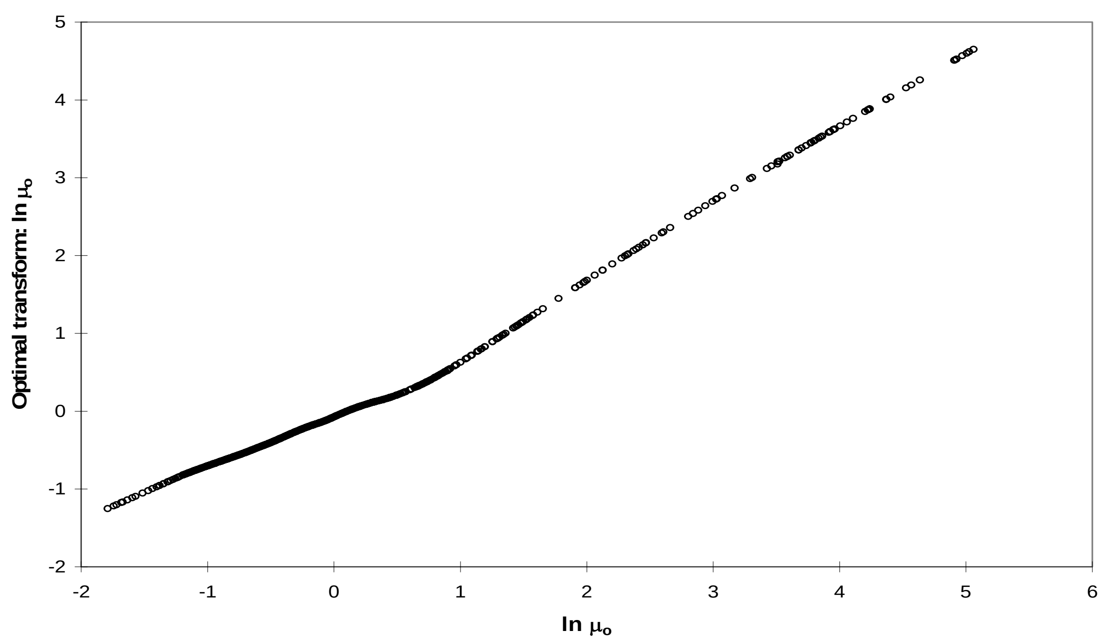

Fig. 25- GRACE optimal transformation of reservoir oil viscosity for saturated reservoir oil (trivariate case for μ_o, ρ_o, and ρ_{sto}).

By curve fitting and tuning methods, the final functional form of transformed dependent and independent variables are provided as follows:

Functional form of the transformed reservoir oil density

$$\rho_{o\_tr} = 5.4855 \cdot 10^{-4} \cdot \rho_o^3 - 0.06551 \cdot \rho_o^2 + 2.6848 \cdot \rho_o - 36.4924 \text{ ,} \qquad (79)$$

Functional form of the transformed stock-tank oil density

$$\rho_{sto\_tr} = 2.818 \cdot 10^{-3} \cdot \rho_{sto}^3 - 0.4394 \cdot \rho_{sto}^2 + 22.797 \cdot \rho_{sto} - 394.3629 \text{ ,} \qquad (80)$$

The summation of transformed independent variables

$$z_{tr} = \rho_{o\_tr} + \rho_{sto\_tr} \text{ ,} \qquad (81)$$

Functional form of the inverse transformation of the reservoir oil viscosity

$$\mu_o = \exp(0.02695 \cdot z_{tr}^3 - 0.2017 \cdot z_{tr}^2 + 1.4409 \cdot z_{tr} - 1.591) \text{ ,} \qquad (82)$$

where ρ_o is reservoir oil density in lb/cu ft, ρ_{sto} is stock-tank oil density in lb/cu ft, and μ_o is reservoir oil viscosity in cp.

The values of ARE and AARE calculated from this case are -0.99% and 25.25%, which are very similar to the previous case. These unimproved statistical error analysis functions lead to the summary that stock-tank oil density should not be included in the proposed saturated oil viscosity correlation equation to prevent the use of a redundant parameter and to pursue the accuracy criteria. The plots of calculated and laboratory-measured saturated oil viscosity are shown in **Fig. 26** and **Fig. 27** for Cartesian and logarithmic coordinates.

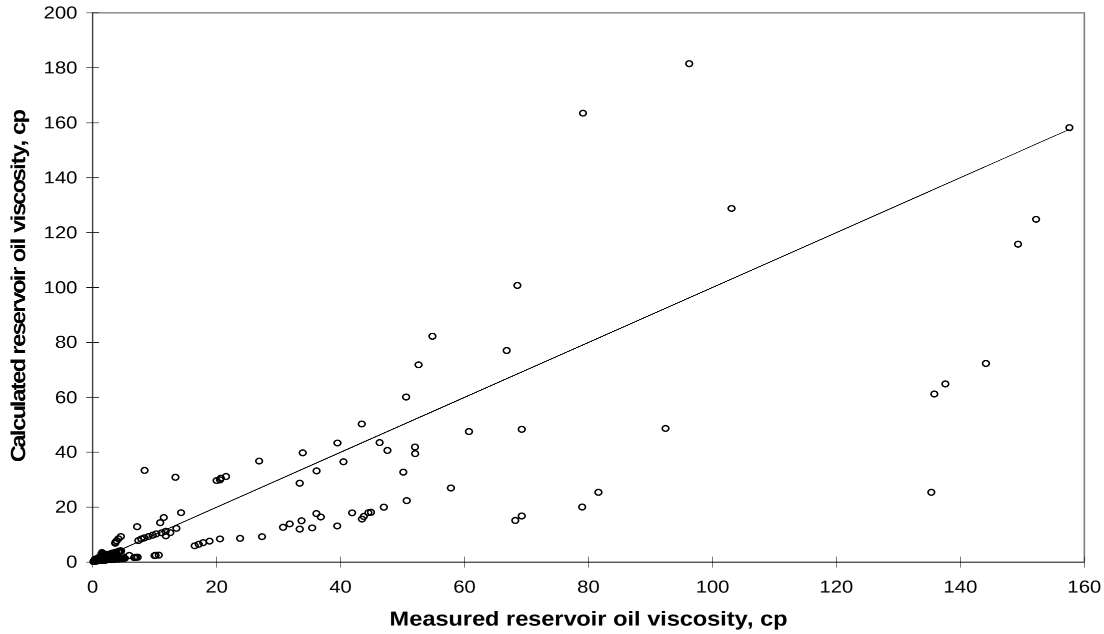

Fig. 26- Calculated and measured saturated oil viscosities are compared on Cartesian coordinates for trivariate case (μ_o, ρ_o, and ρ_{sto}).

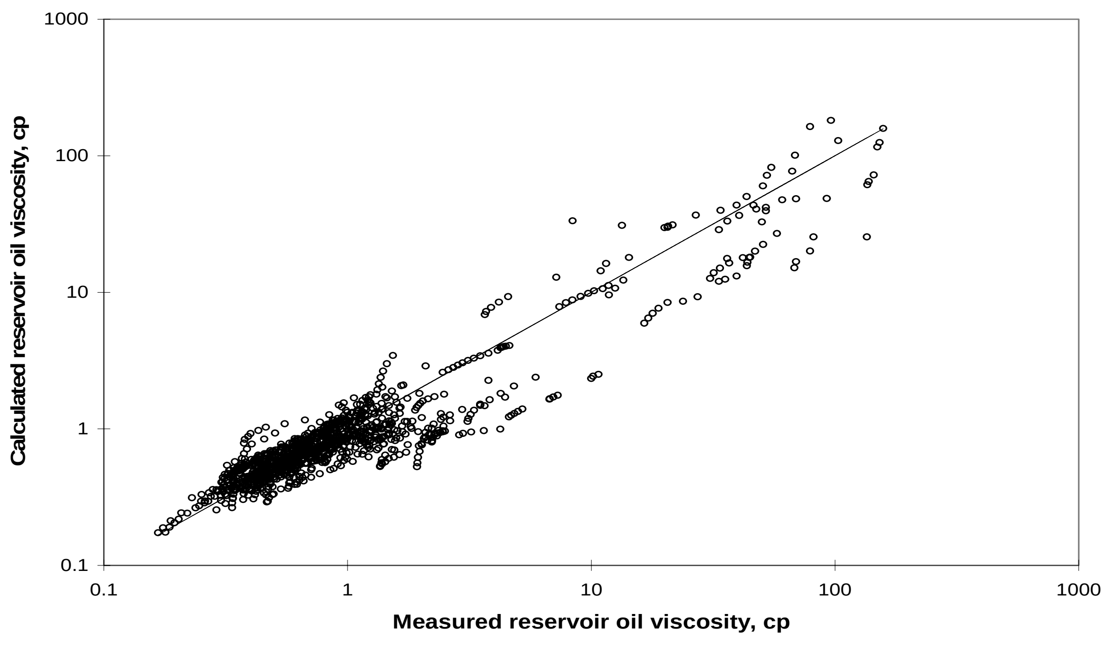

Fig. 27- Calculated and measured saturated oil viscosities are compared on logarithmic coordinates for trivariate case (μ_o, ρ_o, and ρ_{sto}).

Based on the results of the forward stepwise procedure and the ACE algorithm, the saturated oil viscosity correlation equation as a function of reservoir oil density gives the most reliable results of statistical error analysis functions and simplifies the usage of oil viscosity correlation equations. From this reason, the proposed saturated oil viscosity correlation equation in this research is **Eq. 77** and **Eq. 78**.

Errors in Routine Laboratory Measurement of Oil Viscosity

Regarding the high AARE by more than 25%, the controversy about the accuracy of the proposed saturated oil viscosity correlation equation in this research and in several publications is entirely unavoidable. Finding other statistical techniques or using more complicated strategies may not be the right solution to improve the oil viscosity correlation equation at this stage. Based on the discussion in Chapter VI, errors in the measurement of reservoir oil viscosity are the major reasons for the low quality of laboratory-measured oil viscosity and the deficiency in all correlation equations. Certainly, the similar reasons can apply on the proposed correlation equation. To detect these errors, inspection of laboratory PVT data, especially an oil viscosity, is performed in this study. This process reveals a logical explanation for all controversial questions about the error in oil viscosity correlation equations.

Data reconciliation is selected to serve this purpose. The procedures begin with simultaneous adjusting the values of all observations to satisfy a perfect correlation while minimizing the change in each observed value. The data quality of reservoir oil density and viscosity used for correlating the proposed saturated oil viscosity correlation equation is represented in terms of ARA and AARA as shown in **Table 11**.

Table 11- The quality of the data used for correlating the saturated oil viscosity equation is determined by using a data reconciliation technique

Variable	Adjusted laboratory-measured PVT data	
	ARA, %	AARA, %
Reservoir oil density, lb/ft^3	0.0	1.5
Reservoir oil viscosity, cp	2.0	14.7

The extremely low values of ARA and AARA for reservoir oil density indicate no bias in the data and high precision in the laboratory procedures. For reservoir oil viscosity, the positive value of ARA means that the laboratory-measured oil viscosity is less than the actual reservoir oil viscosity. Furthermore, the high value of AARA represents a low precision of laboratory-measured oil viscosity in the database and confirms the existence of errors in routine laboratory measurement of reservoir oil viscosity.

The graphical interpretations of adjusted and laboratory-measured values are created for reservoir oil density and reservoir oil viscosity as shown in **Fig. 28** and **Fig. 29**. If the closer data points are located around a 45^o straight line, the lower adjustment is required in order to fit the correlation perfectly. The data points of reservoir oil density show a lower degree of dispersion, which indicates the higher quality of this parameter in the database.

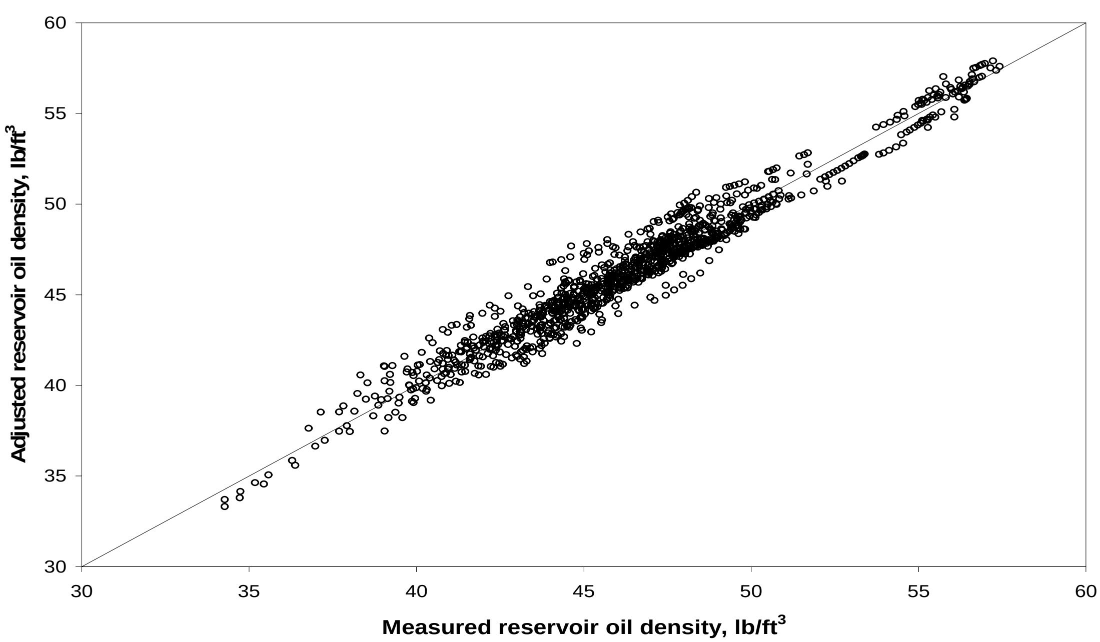

Fig. 28- Adjusted and laboratory-measured reservoir oil densities are compared for saturated reservoir oil.

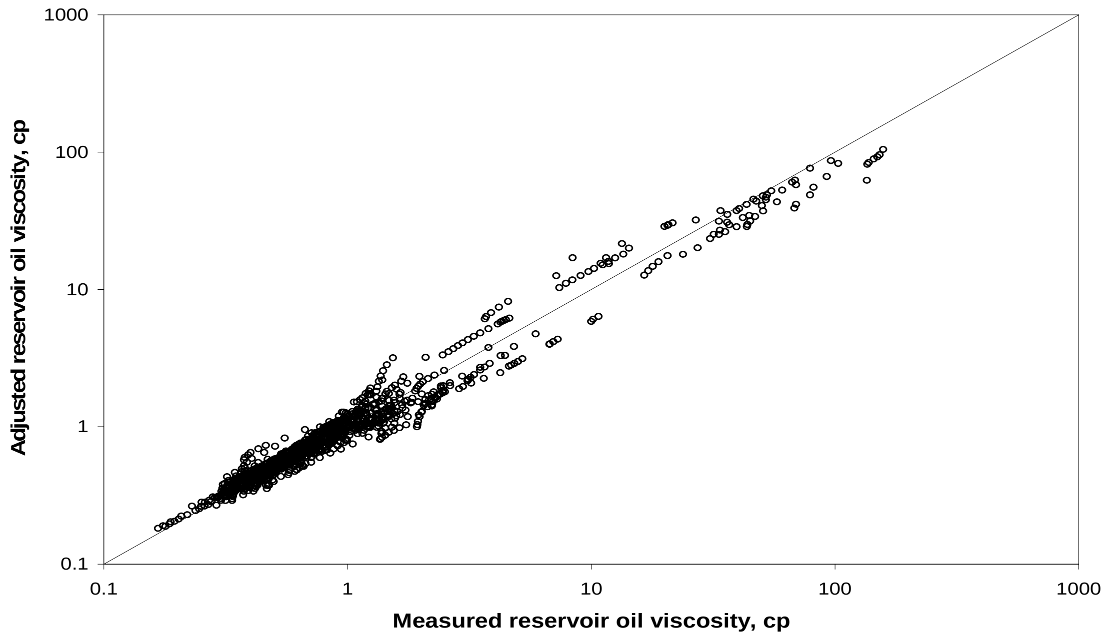

Fig. 29- Adjusted and laboratory-measured reservoir oil viscosities are compared for saturated reservoir oil.

A number of empirical studies show that (1) the error in laboratory-measured oil viscosity is a direct proportion of the type of oil viscosity no matter what type of viscometer is used in the laboratory; (2) comparative measurements of oil viscosity by different laboratories on the same sample can provide the deviation by up to 20%; and (3) laboratory measurements of the viscosity of oil with gas in solution always consist of several sources of error[2]. Based on these statements, there are several hidden factors that cause errors in routine laboratory measurement of oil viscosity. In this research, two major hidden factors, besides high viscous oil and Non-Newtonian behavior as discussed in Chapter VI, are provided as follows:

First, reservoir oil viscosity could be either Newtonian or Non-Newtonian fluid depending on the reservoir conditions. Sometimes, they are in the transient stage while changing the reservoir pressure. This unpredictable transition of reservoir oil viscosity is considered as a hidden factor because there are no effective viscometers that can measure oil viscosity at this transient stage. Therefore, an additional error can be added in laboratory-measured oil viscosity while changing the pressure of viscometers.

Second, another hidden factor is the amount of alphaltenes in petroleum fluid. Asphaltenes are large molecules that do not dissolve in petroleum fluid but are dispersed as collides[15]. The degree of dispersion of alphaltenes indicates whether the petroleum fluid is a Newtonian or Non-Newtonian fluid. Non-Newtonian fluid, generally, has a coarse dispersion of asphaltene particles[42], which substantially escalate the values of reservoir oil viscosity. These conglomerate asphaltenes are a problem that most oil viscometers could not handle.

Other minor hidden factors that possibly affect the properties of oil viscosity, especially Non-Newtonian fluid, and cause error in oil viscosity measurement are temperature, shear rate, measuring conditions, time, pressure, previous history, composition and additives, and special characteristics of dispersions and emulsions[43].

Nowadays, most service companies use a rolling ball viscometer in a routine laboratory measurement to measure oil viscosity. Although the laboratory-measured oil viscosity from these service companies definitely contains the errors, but these errors actually cause by an inefficiency of the viscometers. From this standpoint, the procedures used by service companies for measuring reservoir oil viscosity should not be discredited. The laboratory-measured oil viscosity from the service companies, however, is widely acceptable in petroleum industries and is accurate enough to handle most of engineering calculation.

As long as the erroneous laboratory-measured oil viscosity data have been used for correlating the oil viscosity equations, none of existing statistical techniques or mathematical strategies would create the correlation equations with high efficiency. Therefore, all correlation developers should be concerned about these expected errors from the experimental data and admit the quality of their oil viscosity correlation equations if they have a low level of accuracy.

CHAPTER VIII

CORRELATING VISCOSITY EQUATIONS FOR UNDERSATURATED RESERVOIR OIL

This chapter provides all information about correlating the undersaturated oil viscosity model. The assumption and methodology are similar to the previous chapter. The most concerning issue for developing the undersaturated oil viscosity model is the continuity of bubble point oil viscosity, μ_{ob}, provided by saturated and undersaturated oil viscosity correlation equations. A set of correlation equations would be useless unless the connection at the bubble point oil viscosity is validated. Some published correlation equations[13, 14, 16] are not aware of this important concept and release a set of oil viscosity correlation equations that provides the inconsistent oil viscosities at the bubble point pressure.

The Effective Methodology for Correlating Undersaturated Oil Viscosity Equations

Two familiar formats for undersaturated oil viscosity equations from literature that verify the connection of the bubble point oil viscosity are as follows:

- $\mu_o = \mu_{ob} \left(\frac{p}{p_b} \right)^a$
- $\mu_o = \mu_{ob} + a(p - p_b)$

At the bubble point pressure, the pressure functions are removed; and the undersaturated oil viscosity is equal to the bubble point oil viscosity, which verify the continuity of the correlation equation. The exponent, a, of an undersaturated oil viscosity equation is derived from the plot of oil viscosity function against pressure function and is usually correlated with bubble point pressure, stock-tank oil gravity, bubble point solution gas-oil ratio, and bubble point oil viscosity.

Most published correlation equations use the pressure functions to validate this connection. Oil density, however, has a strong relationship with oil viscosity as discussed in Chapter V; and it should replace a pressure function in an undersaturated oil viscosity correlation equation effectively. Therefore, a breakthrough concept of using oil density function, instead of pressure function, for validation purpose is introduced in this study and is provided as follows:

$$\mu_o = \mu_{ob}\left(\frac{\rho_o}{\rho_{ob}}\right)^a, \quad (83)$$

The plot of viscosity function versus density function on the logarithmic coordinates indicates the slope which nearly is a straight line and the interception at the origin. In this research, slope or exponent, *a*, from 183 PVT reports are correlated with reservoir temperature, separator gas specific gravity, bubble point pressure, bubble point solution gas-oil ratio, bubble point oil density, and stock-tank oil density to determine the most effective equation. Bubble point oil viscosity, however, is not considered as an independent variable because of two reasons. First, laboratory-measured oil viscosity is relatively inconsistent and always has an error. Using an erroneous value as an independent variable would not improve the efficiency of the proposed correlation equation. Second, bubble point oil viscosity calculated from saturated oil viscosity correlation potentially increases an error in the undersaturated oil viscosity model. By using a calculated input rather than a measured input in an equation, the error of the equation would definitely combine with the error made on the calculated input even they has been calculated with the best correlation[21].

A Forward Stepwise Procedure for Correlating the Exponent

The next step is using the forward stepwise procedure to determine the effective independent variable for correlating the exponent, *a*. The procedures begin with finding an independent variable in the first stage that maximizes correlation R^2 values. **Table 12** provides correlation R^2 values for the bivariate cases, which represent the relationship between the transformed exponent and each of transformed laboratory-measured variables.

Table 12- Finding optimal correlation R^2 of transformed variables for bivariate cases (undersaturated oil viscosity correlation)		
Dependent variable	**First stage independent variable**	**Correlation R^2**
ln *a*	γ_g	0.15
	$\ln \gamma_g$	0.15
	T	0.24
	$\ln T$	0.25
	p_b	0.27
	$\ln p_b$	0.27
	R_{Sb}	0.47
	$\ln R_{Sb}$	0.48
	ρ_{sto}	0.62
	$\ln \rho_{sto}$	0.61
	ρ_{ob}	0.71
	$\ln \rho_{ob}$	0.71

Based on the results, the maximal correlation R^2 value is the results of correlating the exponent, *a*, with the bubble point oil density function. Therefore, bubble point oil density has a robust relationship with the exponent, *a*, and is used as an independent variable in the first stage. For trivariate cases, the correlation R^2 values and the improvement percentage are provided in **Table 13**.

Table 13- Finding optimal correlation R^2 of transformed variables for trivariate cases (undersaturated oil viscosity correlation)				
Dependent variable	**First stage independent variable**	**Second stage independent variable**	**Correlation R^2**	**Improvement, %**
ln *a*	$\ln \rho_{ob}$	T	0.716	0.61
		$\ln T$	0.716	0.68
		ρ_{sto}	0.721	1.26
		$\ln \rho_{sto}$	0.720	1.25
		γ_g	0.724	1.71
		$\ln \gamma_g$	0.724	1.72
		R_{Sb}	0.726	2.06
		$\ln R_{Sb}$	0.726	2.08
		p_b	0.746	4.84
		$\ln p_b$	0.748	5.12

The results indicate that a bubble point pressure improves the correlation R^2 value of the existing model up to 5.12% and could be used as an independent variable in the second stage for correlating the exponent of an undersaturated oil viscosity equation. This small improvement of the correlation R^2 value is probably not increase the performance of the proposed correlation equation. Searching for an independent variable in the third stage is continued in **Table C-2**; and the results of correlation R^2 values and improvement percentage indicate that remaining independent variables do not improve the correlation R^2 value of the previous model. Further most of them degrade the correlation performance as shown by the negative values of the improvement percentage. Therefore, the forward stepwise procedure is stopped at the trivariate case; and the proposed equation for predicting the exponent, *a*, is a function of a bubble point oil density, as a main contributor, and a bubble point pressure, as a secondary contributor.

In this chapter, two equations for predicting the exponent of undersaturated oil viscosity correlation are proposed and compared their performance in terms of statistical and graphical error analysis to determine the most effective equation. The first equation is correlated as a function of a bubble point oil density only, while the second equation is correlated by using both bubble point oil density and bubble point pressure. Either of these equations that provide the most accurate estimation of undersaturated oil viscosity would be selected as the proposed correlation equation for calculating the exponent of an undersaturated oil viscosity correlation equation.

For bivariate case, the graphical interpretation of optimal transformations for the dependent variable, the exponent, and an independent variable, a bubble point oil density, are provided by the GRACE software and shown in **Fig. 30** and **Fig. 31**. Both plots look very similar and show the trend at some degrees of smoothness, which is fit with the simple polynomial equations easily.

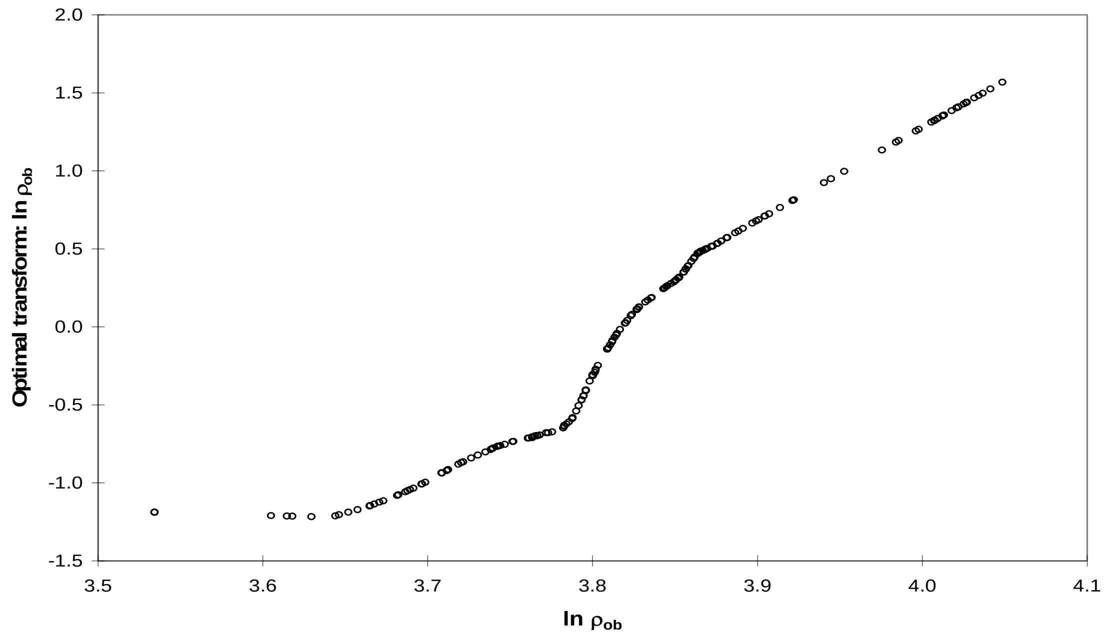

Fig. 30- GRACE optimal transformation of bubble point oil density for undersaturated reservoir oil (bivariate case for μ_o and ρ_o).

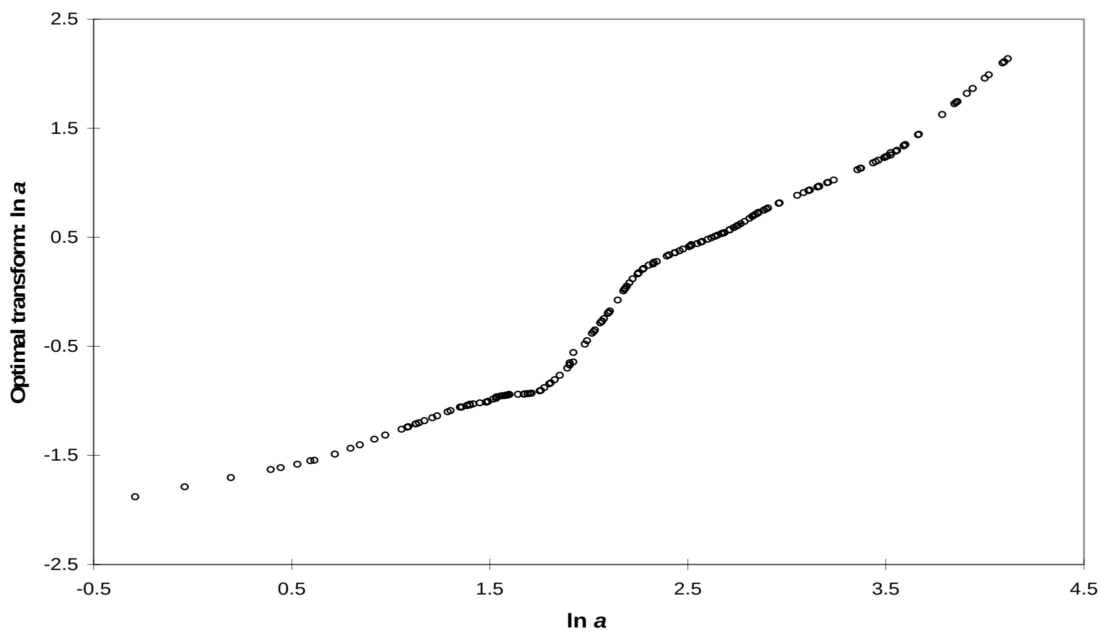

Fig. 31- GRACE optimal transformation of the exponent for undersaturated reservoir oil (bivariate case for μ_o and ρ_o).

Curve fitting and tuning processes are used to determine the functional forms of the transformed bubble point oil density and the inverse transform of the exponent. The functional forms are simply shown as the third order polynomial equations as follows:

Functional form of the transformed bubble point oil density

$$\rho_{ob\_tr} = -68.1347 \ln \rho_{ob}^3 + 783.3222 \ln \rho_{ob}^2 - 2992.3068 \ln \rho_{ob} + 3797.6 \text{,.. (84)}$$

Functional form of the inverse transformation of the exponent

$$a = \exp\left(0.18019 \cdot \rho_{ob\_tr}^3 + 0.13781 \cdot \rho_{ob\_tr}^2 + 0.73906 \cdot \rho_{ob\_tr} + 2.5181\right) \text{,...... (85)}$$

where ρ_{ob} is bubble point oil density in lb/cu ft and a is the exponent.

All parameters in **Eq. 83**, which are the calculated exponent, a, the calculated bubble point oil viscosity from the proposed saturated oil viscosity correlation equation, and the laboratory-measured oil density function, are required to calculate an undersaturated oil viscosity. The values of ARE and AARE for the proposed undersaturated oil viscosity correlation equation are -6.92% and 31.52%. The graphical interpretation for calculated and laboratory-measured oil viscosities are shown in **Fig. 32** and **Fig. 33** for Cartesian and logarithmic coordinates.

The negative value of ARE indicates that calculated oil viscosity from the proposed correlation equation is usually lower than the laboratory-measured value. The high value of AARE shows a high deviation of predicted oil viscosity, which causes mainly by the erroneous inputs in the undersaturated oil viscosity correlation equation and the low quality of undersaturated oil viscosity data from the database. The correctness of this equation, however, is better than that of published correlation equations.

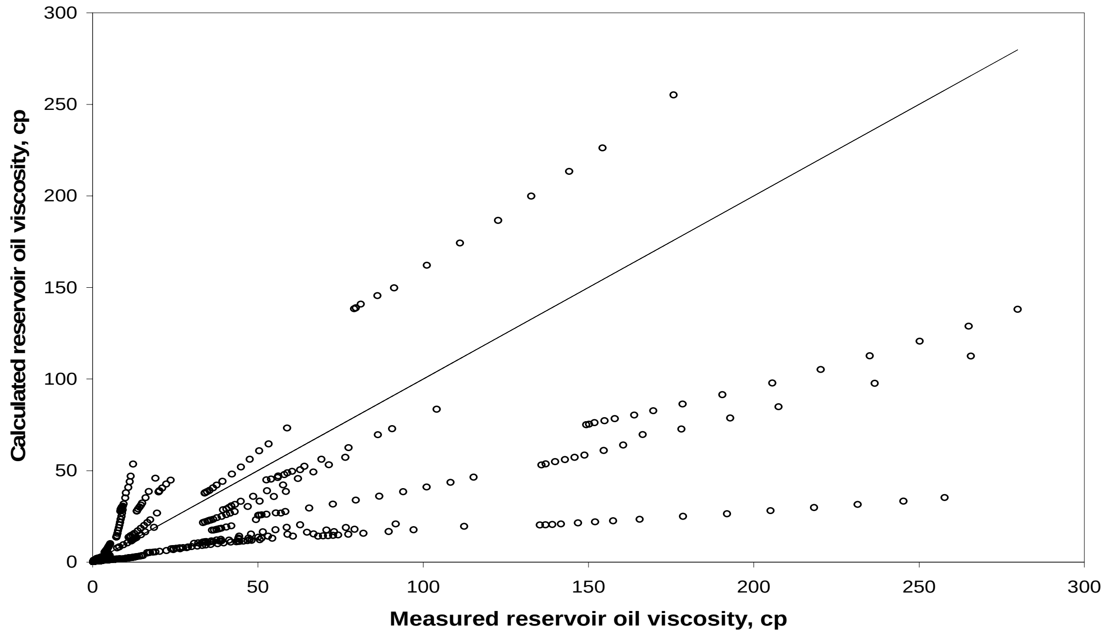

Fig. 32- Calculated and measured undersaturated oil viscosity data are compared on Cartesian coordinates for bivariate case (μ_o and ρ_o).

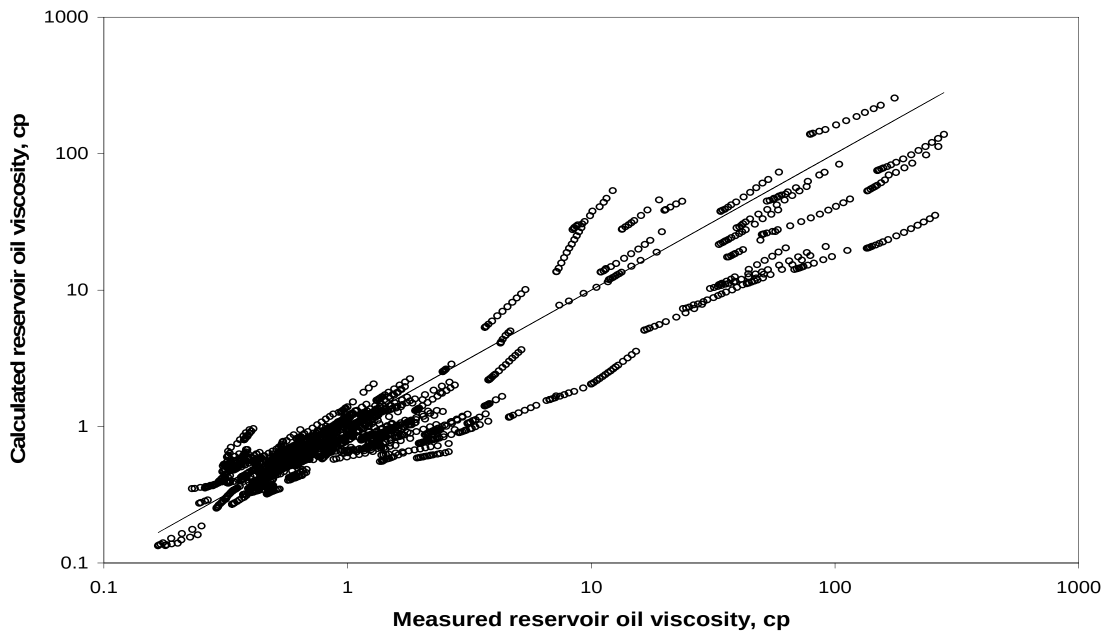

Fig. 33- Calculated and measured undersaturated oil viscosity data are compared on logarithmic coordinates for bivariate case (μ_o and ρ_o).

The data points are equally scattered and reasonably closed to a 45^{o} straight line, which indicates random distribution and consistency of the proposed undersaturated oil viscosity correlation equation.

For the trivariate case, a bubble point pressure is used as an independent variable in the second stage to determine the improvement of the proposed correlation equation. The optimal transformations of a bubble point oil density, a bubble point pressure, and the exponent, *a*, are shown in **Fig. 34**, **Fig. 35**, and **Fig. 36**, respectively. The shapes of the transformed bubble point oil density and the transformed exponent are similar to the previous case. Noticeably, the similar shape of transformed exponent indicates the low influence of adding a bubble point pressure into the proposed correlation equation. From this reason, a bubble point pressure does not significantly improve the performance of the proposed correlation equation and is probably not an effective parameter for correlating the exponent, *a*, in this research.

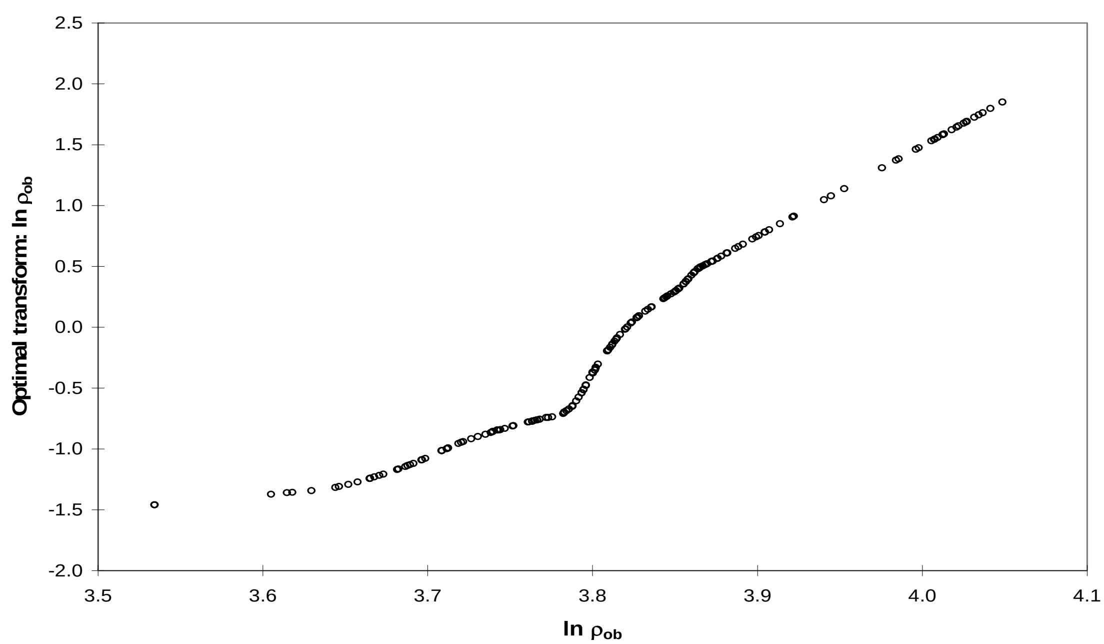

Fig. 34- GRACE optimal transformation of bubble point oil density for undersaturated reservoir oil (trivariate case for μ_o, ρ_o, and p_b).

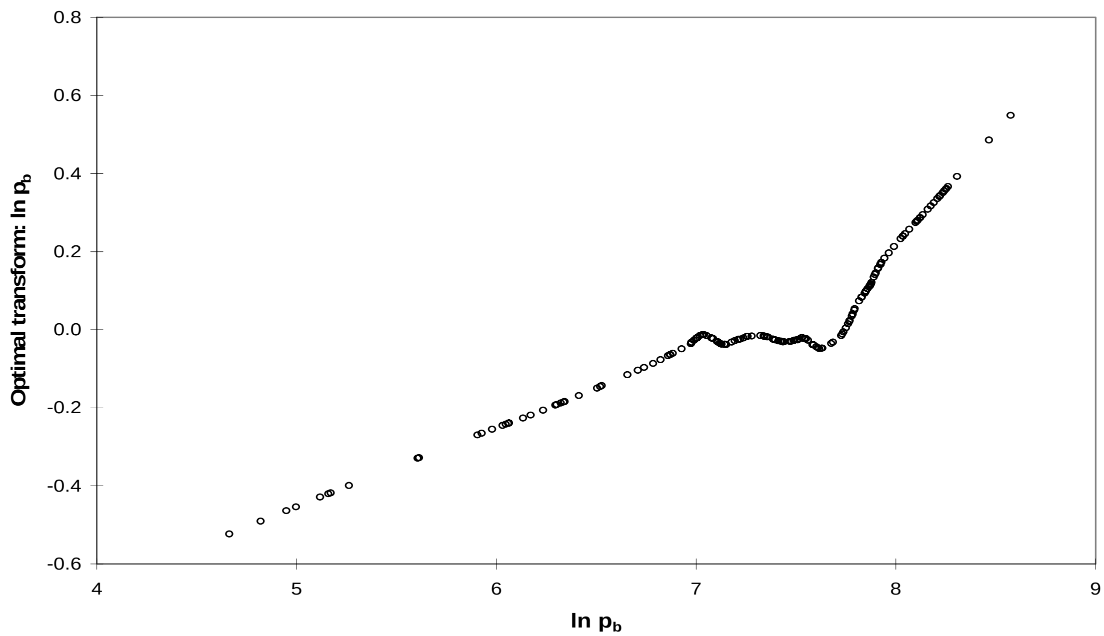

Fig. 35- GRACE optimal transformation of bubble point pressure for undersaturated reservoir oil (trivariate case for μ_o, ρ_o, and p_b).

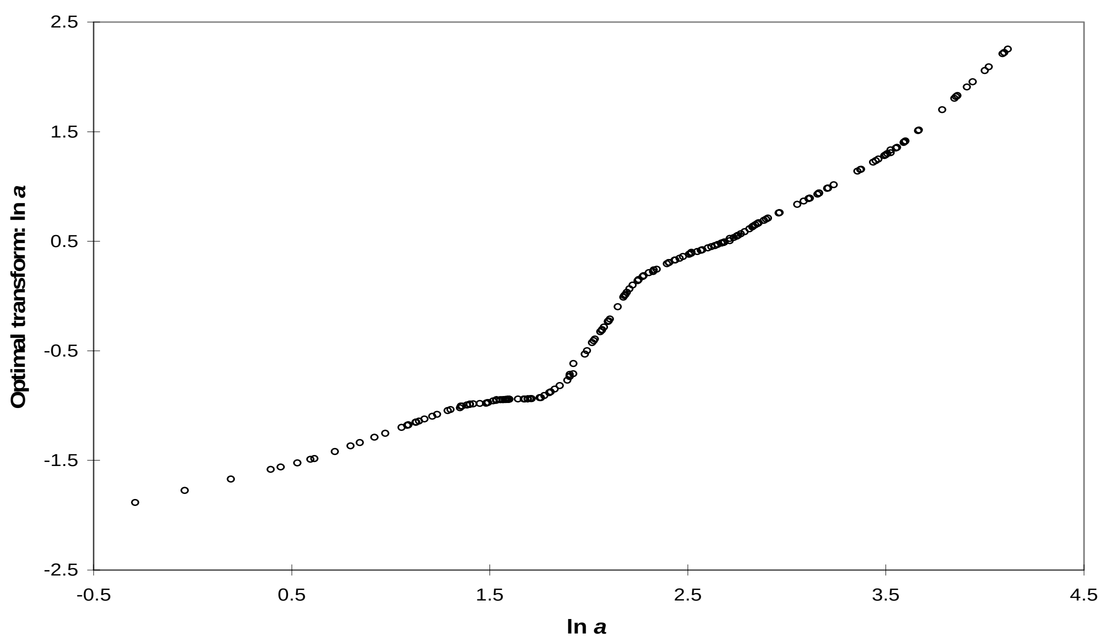

Fig. 36- GRACE optimal transformation of the exponent for undersaturated reservoir oil (trivariate case for μ_o, ρ_o, and p_b).

The final functional forms of transformed dependent and independent variables are provided as follows:

Functional form of the transformed bubble point oil density

$$\rho_{ob\_tr} = -61.5246 \ln \rho_{ob}^3 + 709.6163 \ln \rho_{ob}^2 - 2717.621 \ln \rho_{ob} + 3455.599 \text{ ,. (86)}$$

Functional form of the transformed bubble point pressure

$$p_{b\_tr} = 0.0365 \ln p_b^2 - 0.29579 \ln p_b + 0.19966 \text{ ,....................................... (87)}$$

The summation of transformed independent variables

$$z_{tr} = \rho_{ob\_tr} + p_{b\_tr} \text{ ,... (88)}$$

Functional form of the inverse transformation of the exponent

$$a = \exp\left(0.12572 \cdot z_{tr}^3 + 0.04923 \cdot z_{tr}^2 + 0.7801 \cdot z_{tr} + 2.3724\right) \text{,........................ (89)}$$

where ρ_{ob} is bubble point oil density in lb/cu ft and p_b is bubble point pressure in psia.

The values of ARE and AARE, which are -6.79% and 31.45%, indicate a small improvement. The plots of calculated versus laboratory-measured undersaturated oil viscosity as shown in **Fig. 37** and **Fig. 38** for Cartesian and logarithmic coordinates are also very similar to the plots of the previous case. These results indicate the low improvement of the performance by adding bubble point pressure into the proposed equation. From this reason, the proposed correlation equation for the exponent of an undersaturated oil viscosity correlation equation is provided in terms of a bubble point oil density only as shown in **Eq. 84** and **Eq. 85**.

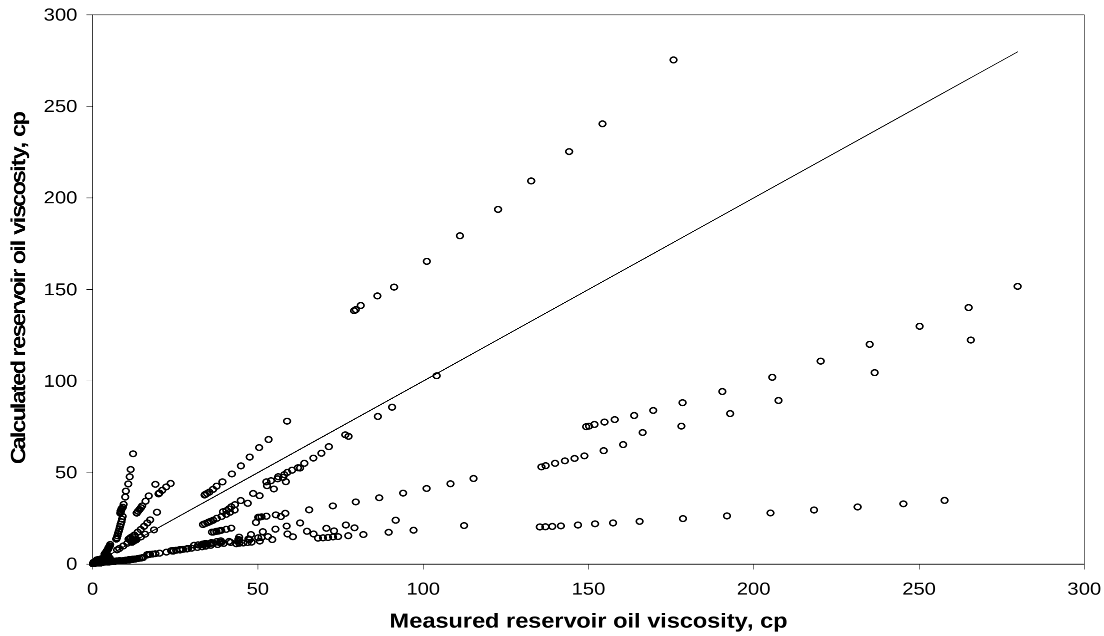

Fig. 37- Calculated and measured undersaturated oil viscosity data are compared on Cartesian coordinates for trivariate case (μ_o, ρ_o, and p_b).

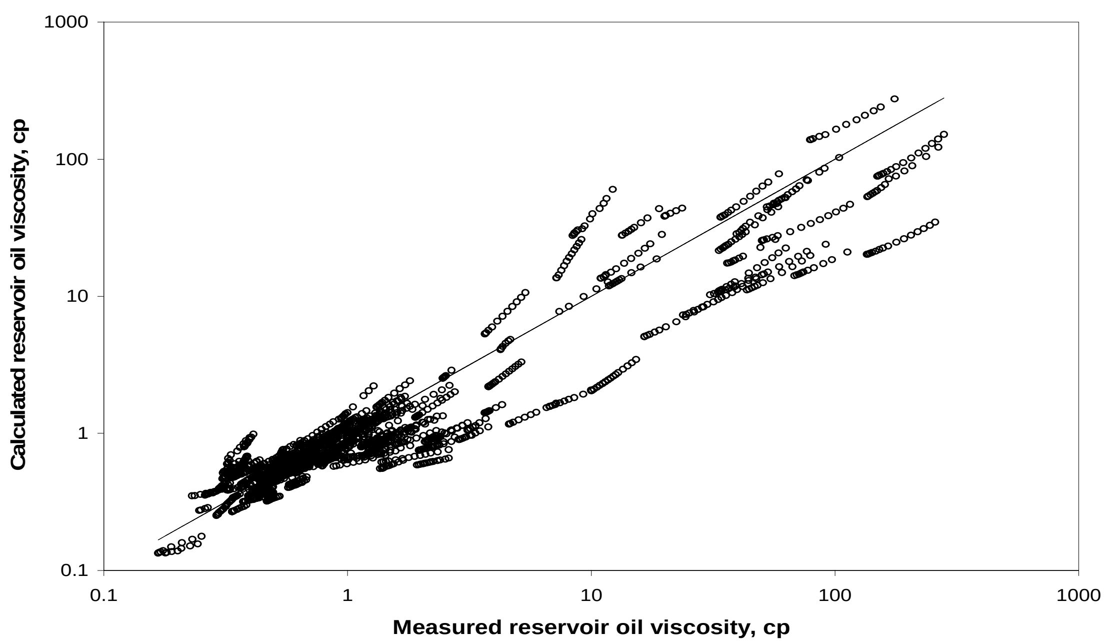

Fig. 38- Calculated and measured undersaturated oil viscosity data are compared on logarithmic coordinates for trivariate case (μ_o, ρ_o, and p_b).

Evaluation of Data Quality Using Data Reconciliation Technique

Table 14 shows the results of data reconciliation technique for the dependent variable and independent variables. The bubble point oil density shows the low values of ARA and AARA which indicates a low bias and a high precision of this parameter. For the exponent of an undersaturated oil viscosity correlation equation, the relatively high value of AARA represents the consequent error from using of laboratory-measured oil viscosity data to derive this parameter. This problem could provide a sequent effect on the accuracy of the proposed undersaturated oil viscosity correlation equation in this research.

Table 14- The quality of data used for correlating an exponent, *a*, equation is determined by using a data reconciliation technique

Variable	Adjusted laboratory-measured PVT data	
	ARA, %	AARA, %
Bubble point oil density, lb/ft^3	4.2	6.8
Exponent, *a*	7.6	23.9

The graphical interpretations for adjusted and measured values of a bubble point oil density and the exponent are shown in **Fig. 39** and **Fig. 40**. The low dispersion of adjusted bubble point oil density around a 45^o straight line indicates the least amount of adjustment that requires for correlating the perfect equation. This result confirms the usefulness and the precision of bubble point oil density used in the proposed correlation equation. The relatively high deviation of reconciled values indicates the low quality of the exponent data, which originally are derived from oil viscosity and oil density functions. The oil density function has a high level of reliability supported by the results of data reconciliation technique. Therefore, the sources of imprecision and deficiency of the exponent definitely come from the oil viscosity function.

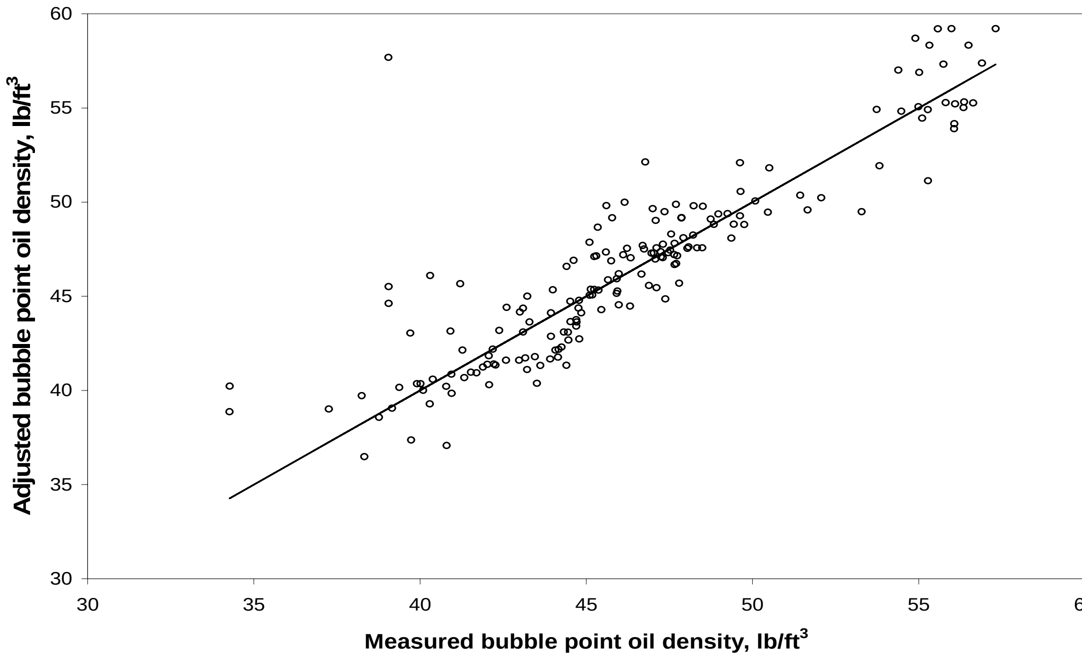

Fig. 39- Adjusted and laboratory-measured bubble point oil density data are compared for undersaturated reservoir oil.

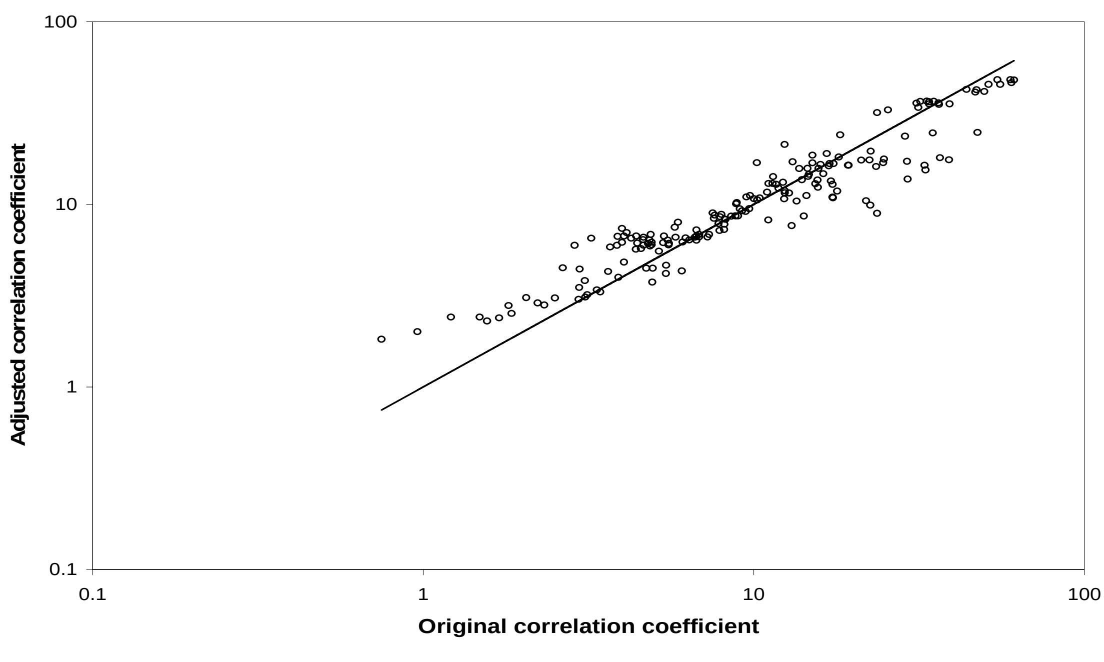

Fig. 40- Adjusted and original exponent data are compared for undersaturated reservoir oil.

Testing the Proposed Undersaturated Oil Viscosity Correlation Equations

The high percentage error in the proposed undersaturated oil viscosity correlation equation causes by using the calculated bubble point oil viscosity in the model. The proposed saturated oil viscosity correlation equation used for calculating the bubble point oil viscosity contains the error up to 25%, which considers as a high deviation. A bubble point oil viscosity, however, is a mandatory parameter and could not be removed from the proposed undersaturated oil viscosity correlation equation. Therefore, the actual performance of the proposed undersaturated oil viscosity correlation equation without the effect of high erroneous input parameter might be questionable.

Laboratory-measured bubble point oil viscosity, which is considered as the reliable information at this time, can replace the calculated bubble point oil viscosity from the proposed saturated oil viscosity correlation equation to determine the true efficiency of the proposed undersaturated oil viscosity correlation equation. **Table 15** shows the results of statistical error analysis for the proposed and published undersaturated oil viscosity correlation equations by using laboratory-measured bubble point oil viscosity, instead of calculated bubble point oil viscosity, as an input parameter.

Table 15- A performance of undersaturated oil viscosity correlation using laboratory-measured bubble point oil viscosity (183 PVT reports/1968 data points)

Undersaturated oil viscosity correlations	Predicted undersaturated oil viscosity	
	ARE, %	AARE, %
This work (2005)	-0.81	3.72
Standing (1977)	-2.47	4.54
Khan *et al.* (1987)	-1.49	4.60
Almehaideb (1997)	-1.15	5.60
Petrosky and Farshad (1995)	-2.54	5.69
Kartoatmodjo and Schmidt (1991)	-4.96	6.04
De Ghetto, Paone, and Villa (1994)	-2.39	6.30
Elsharkawy and Alikhan (1999)	-2.47	7.06
Vasquez and Beggs (1980)	3.62	7.45
Labedi (1992)	1.42	7.68
Elsharkwy and Gharbi (2001)	6.52	14.40
Al-Khafaji, Abdul-Majeed, and Hassoon (1987)	59.93	62.43
Dindoruk and Christman (2001)	88.53	91.05

The results of the statistical error analysis indicate that the proposed correlation equation has the lowest values of ARE and AARE. Among the published correlation equations, the Standing[4] and the Khan *et al*[11, 12] correlation equations provide an outstanding result for predicting undersaturated oil viscosity. These results can imply that using more accurate bubble point oil viscosity would tremendously improve the performance of undersaturated oil viscosity correlation equations and would achieve the most accurate prediction with the proposed correlation equation.

Very interesting, the Dindoruk and Christman correlation equation[29], which provides the best prediction as indicated in Chapter VI, has the incredibly low accuracy when laboratory-measured bubble point oil density is used as an input parameter. This correlation equation was developed by using a low range oil viscosity value of less than 10 cp; therefore, a huge deviation of the predicting values would definitely happen when the equation is applied with the high value of oil viscosity at the bubble point pressure from the database. The deficiency and the unreliability in the Dindoruk and Christman correlation equation[29] cause mainly by a low range oil viscosity in their database and malfunction of their correlation equation.

The graphical interpretation for calculated undersaturated oil viscosity from the proposed correlation equation using laboratory-measured bubble point oil viscosity and laboratory-measured values, as shown in **Fig. 41** and **Fig. 42** for Cartesian and logarithmic coordinates, show that most data points are very close to a 45^o straight line, which indicates the high accuracy of the proposed undersaturated oil viscosity correlation equation. The dispersion of data is very steady for all oil viscosity values, which indicates the consistence of the proposed equation; whereas most published correlation equations has high inconsistent results, especially at high viscosity ranges. Therefore, the proposed correlation equation provides the best overall efficiency when it is applied with either calculated or experimental bubble point oil viscosities, has a wider range of validity, and is superior to other published correlation equations for predicting undersaturated oil viscosity. Additional information of the graphical interpretations from all published correlation equations is available in **Appendix D** of this dissertation.

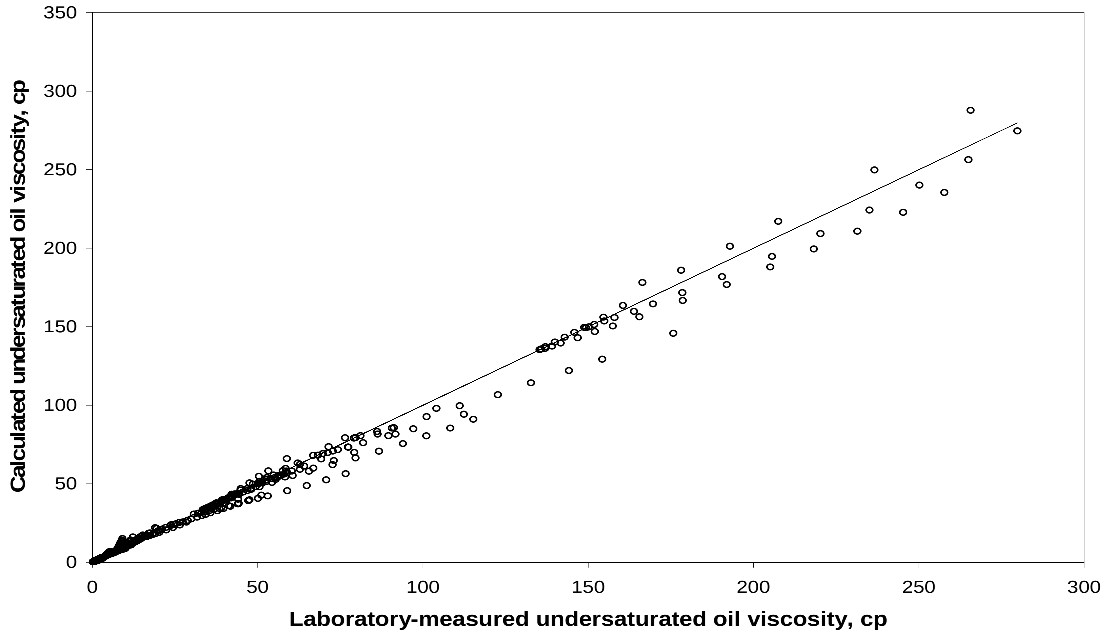

Fig. 41- Calculated undersaturated oil viscosity data using measured bubble point oil viscosity as an input are compared with measured values on Cartesian scales.

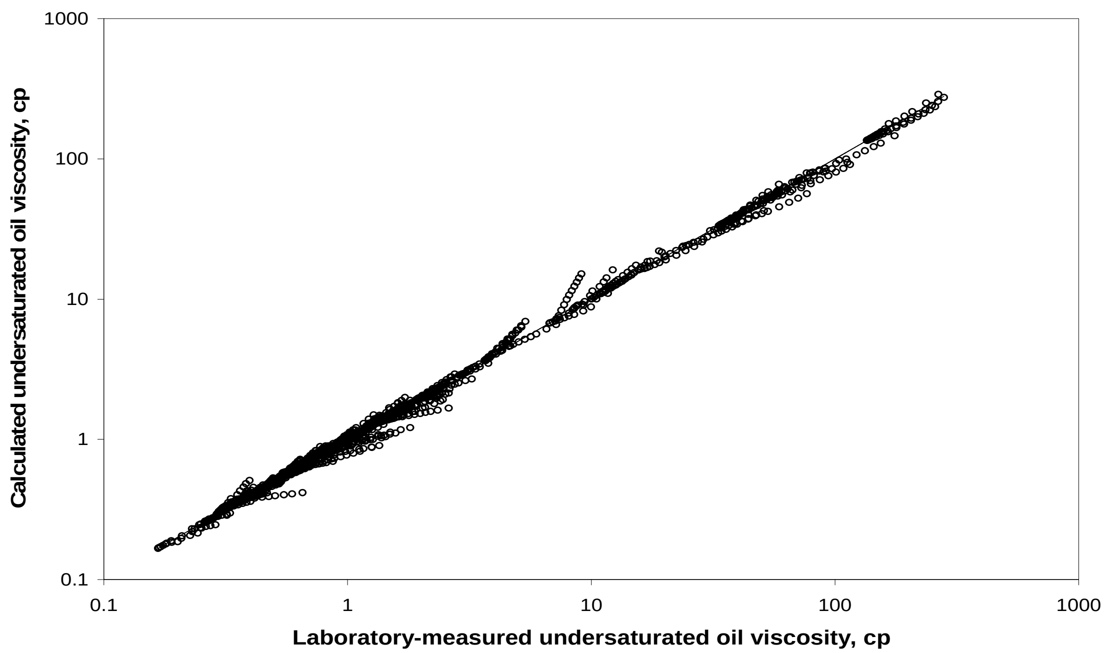

Fig. 42- Calculated undersaturated oil viscosity data using measured bubble point oil viscosity as an input are compared with measured values on logarithmic scales.

CHAPTER IX

TESTING THE PERFORMANCE OF THE RESERVOIR OIL VISCOSITY CORRELATION EQUATIONS

This chapter provides all supplementary information about the testing results of the proposed correlation equations when they are applied with any ranges of reservoir parameters. Both saturated and undersaturated oil viscosity correlation equations are tested at different ranges of stock-tank oil gravity, reservoir temperature, bubble point solution gas-oil ratio, and bubble point oil viscosity. To verify the efficiency of the proposed correlation equations at more specific ranges of oil viscosity, the bubble point oil viscosity is divided into 3 domains, which are the values of less than 1 cp, between 1 to 10 cp, and of greater than 10 cp.

The procedures begin with sorting and dividing the database into subsets of equal ranges. Then the graphical interpretation of these subsets and the statistical error analysis functions, ARE and AARE, are provided in **Fig. 43** through **Fig. 54** for saturated reservoir oil and in **Fig. 55** through **Fig. 66** for undersaturated reservoir oil. Other correlation equations from literature are also tested with the similar subsets and plotted in the same figure for comparing their performance with the performance of the proposed equations. The selected published correlation equations are the Beggs and Robinson[4], the Vasquez and Beggs[6], the Dindoruk and Christman[29], the De Ghetto, Paone, and Villa[21], and the Petrosky and Farshad[23] correlation equations. The numerical results of ARE and AARE at any ranges of reservoir parameters are available in **Appendix E** of this dissertation.

Based on these graphical interpretations, the proposed correlation equations indicate the relatively better results for overall reservoir conditions than other published correlation equations. This superiority indicates the high reliability and consistency of the proposed correlation equations, which are the most aspects in this research.

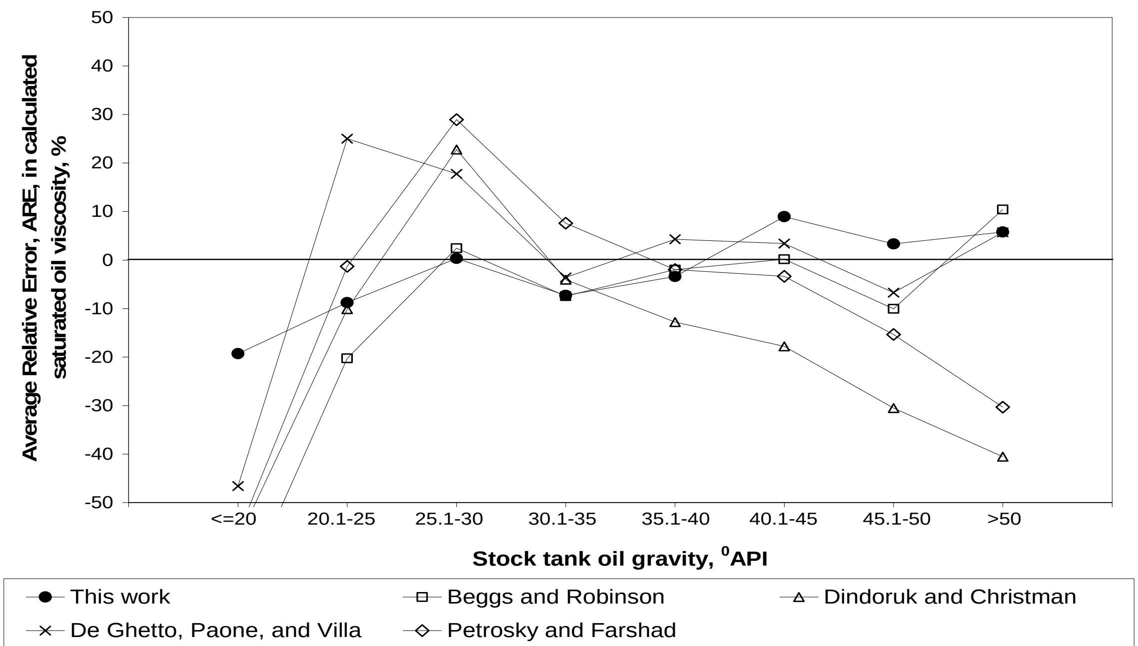

Fig. 43- The reliability of the saturated oil viscosity correlation (regarding ARE) across the range of stock-tank oil gravity.

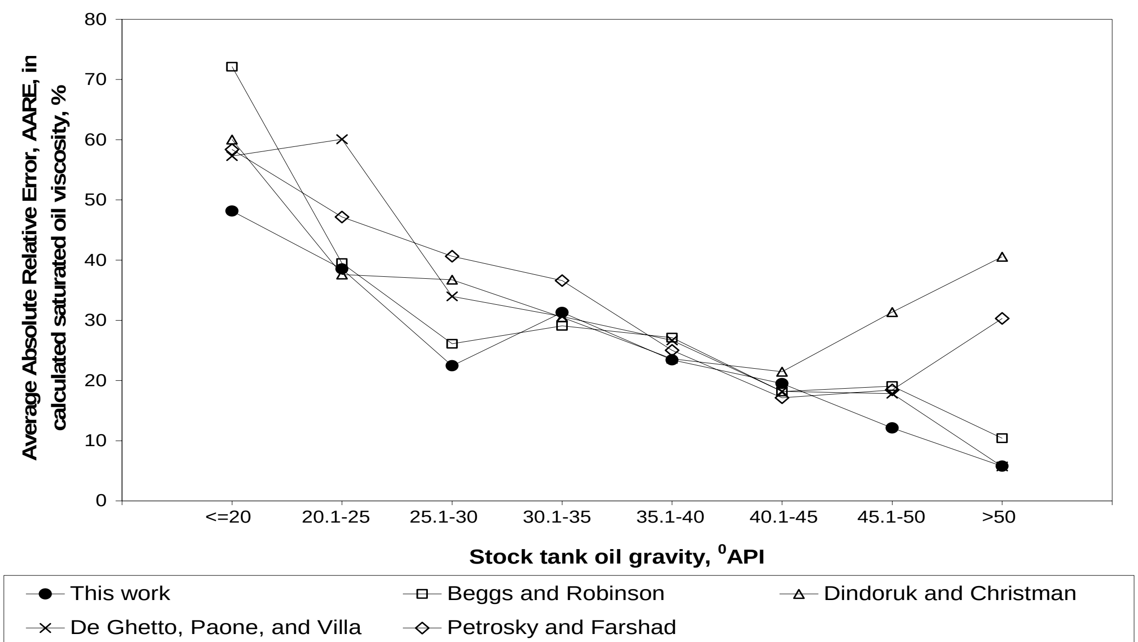

Fig. 44- The reliability of the saturated oil viscosity correlation (regarding AARE) across the range of stock-tank oil gravity.

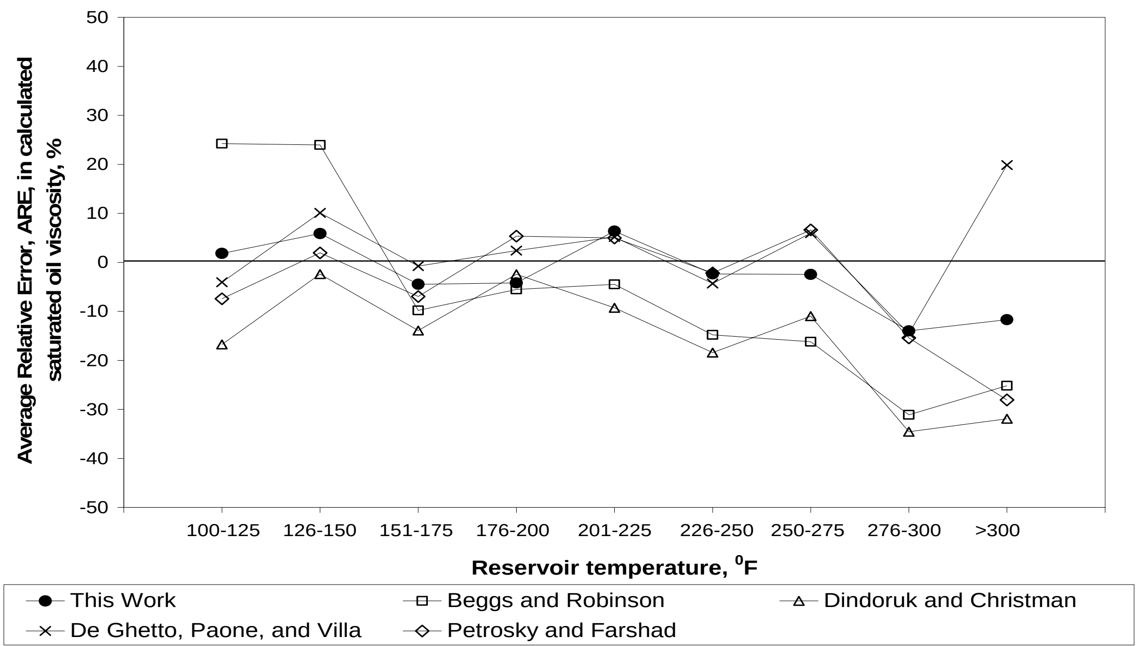

Fig. 45- The reliability of the saturated oil viscosity correlation (regarding ARE) across the range of reservoir temperature.

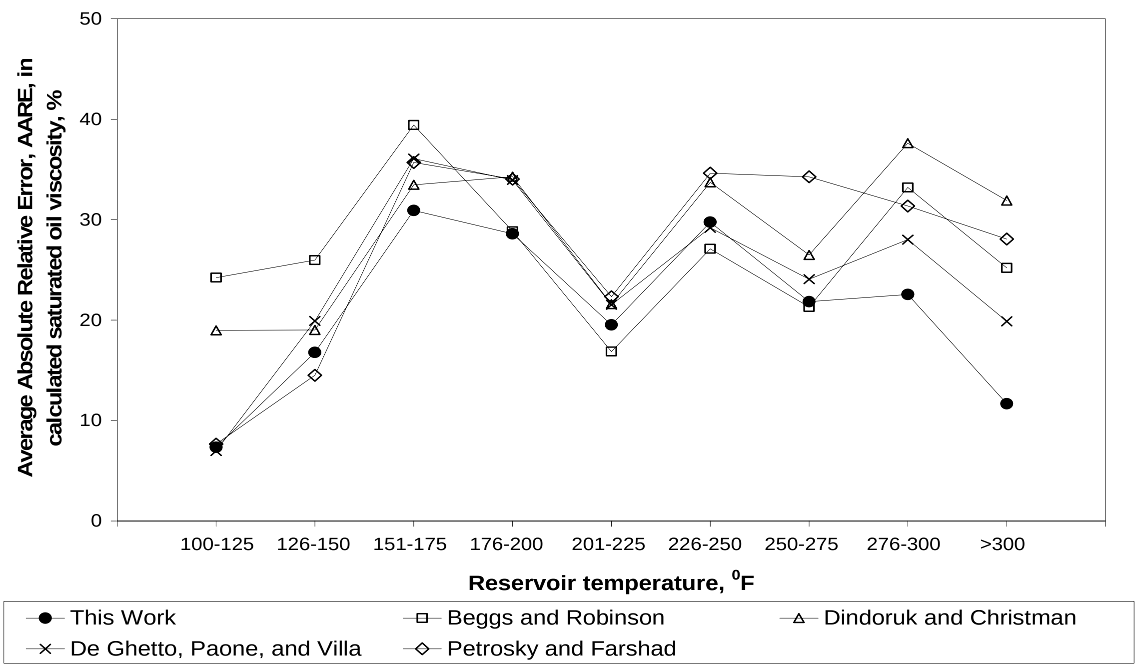

Fig. 46- The reliability of the saturated oil viscosity correlation (regarding AARE) across the range of reservoir temperature.

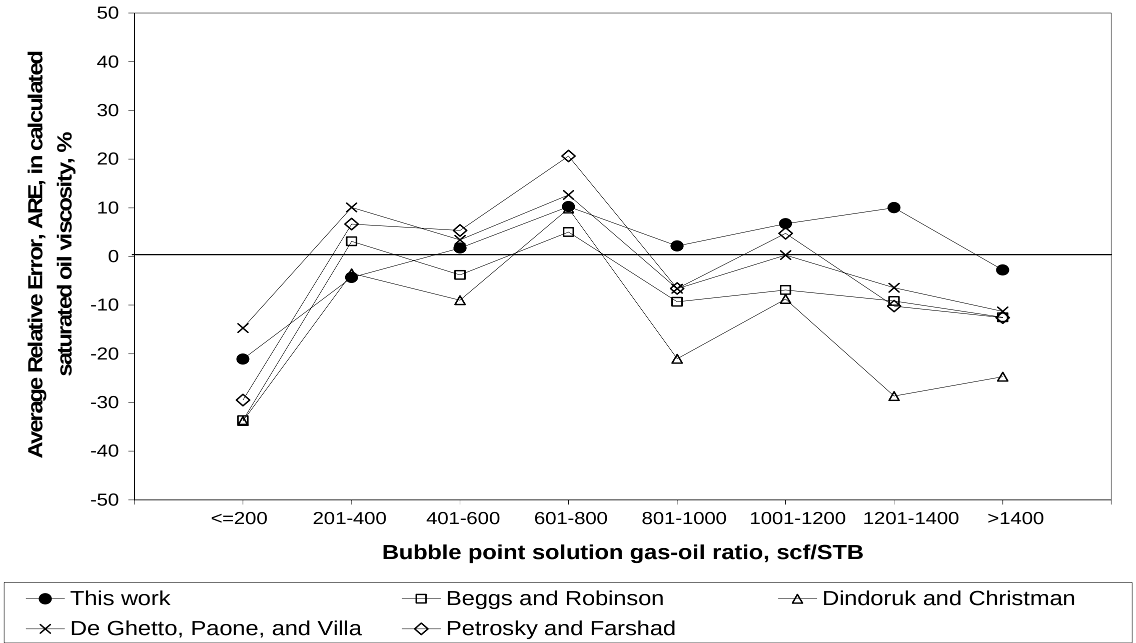

Fig. 47- The reliability of the saturated oil viscosity correlation (regarding ARE) across the range of bubble point solution gas-oil ratio.

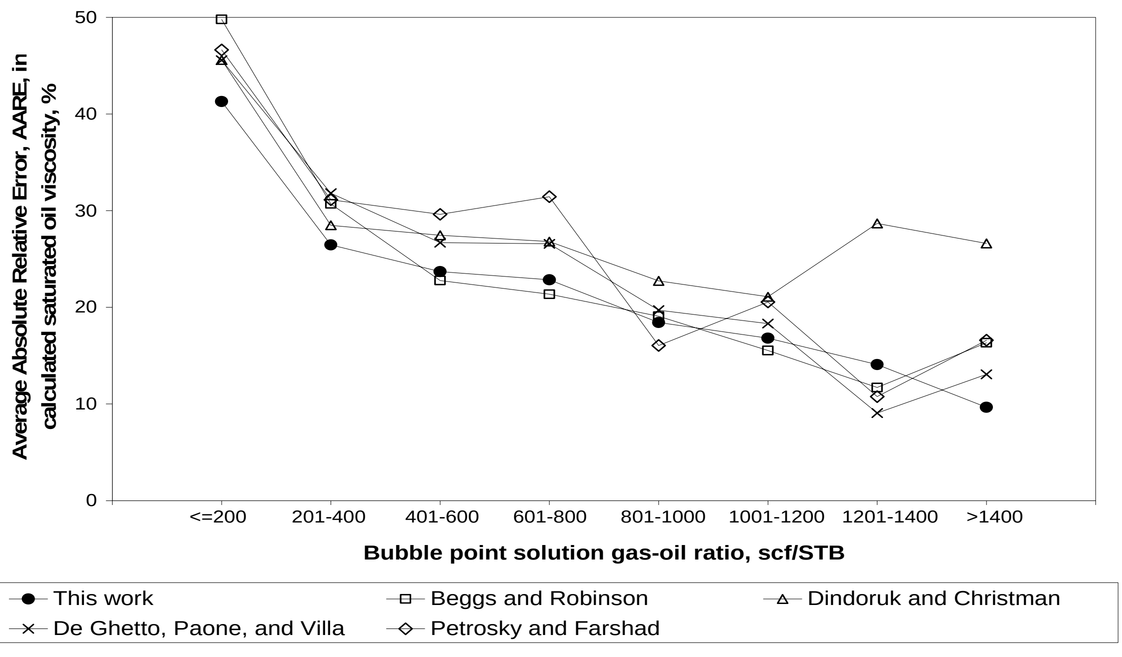

Fig. 48- The reliability of the saturated oil viscosity correlation (regarding AARE) across the range of bubble point solution gas-oil ratio.

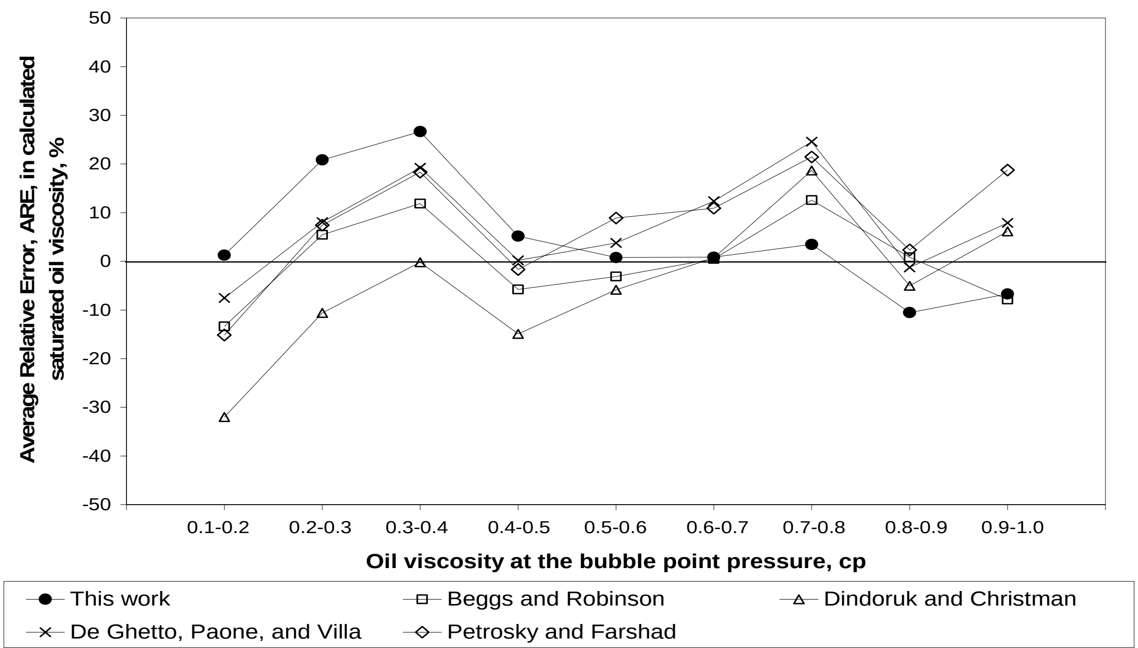

Fig. 49- The reliability of the saturated oil viscosity correlation (regarding ARE) across the range of oil viscosity at the bubble point pressure (μ_b≤1cp).

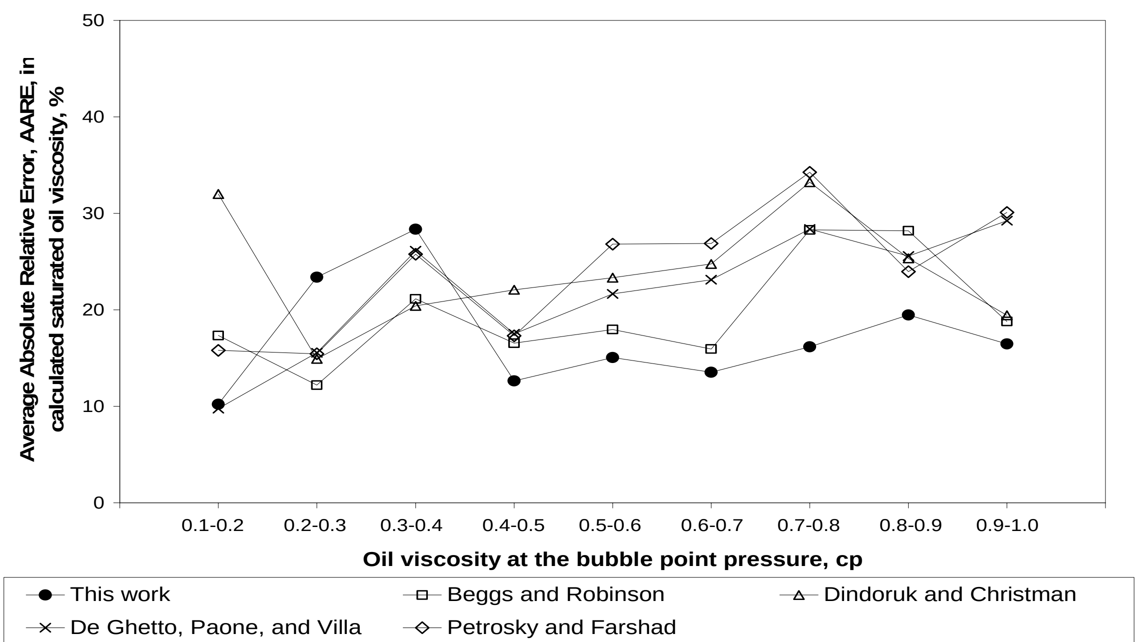

Fig. 50- The reliability of the saturated oil viscosity correlation (regarding AARE) across the range of oil viscosity at the bubble point pressure (μ_b≤1cp).

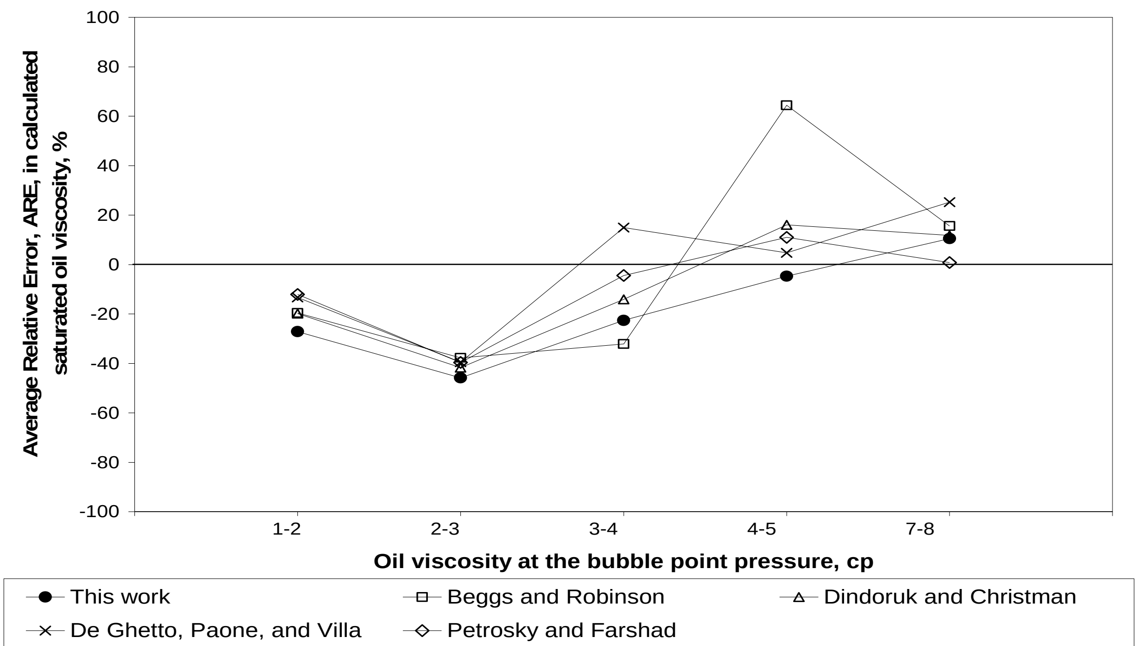

Fig. 51- The reliability of the saturated oil viscosity correlation (regarding ARE) across the range of oil viscosity at the bubble point pressure (1<μ_b≤10cp).

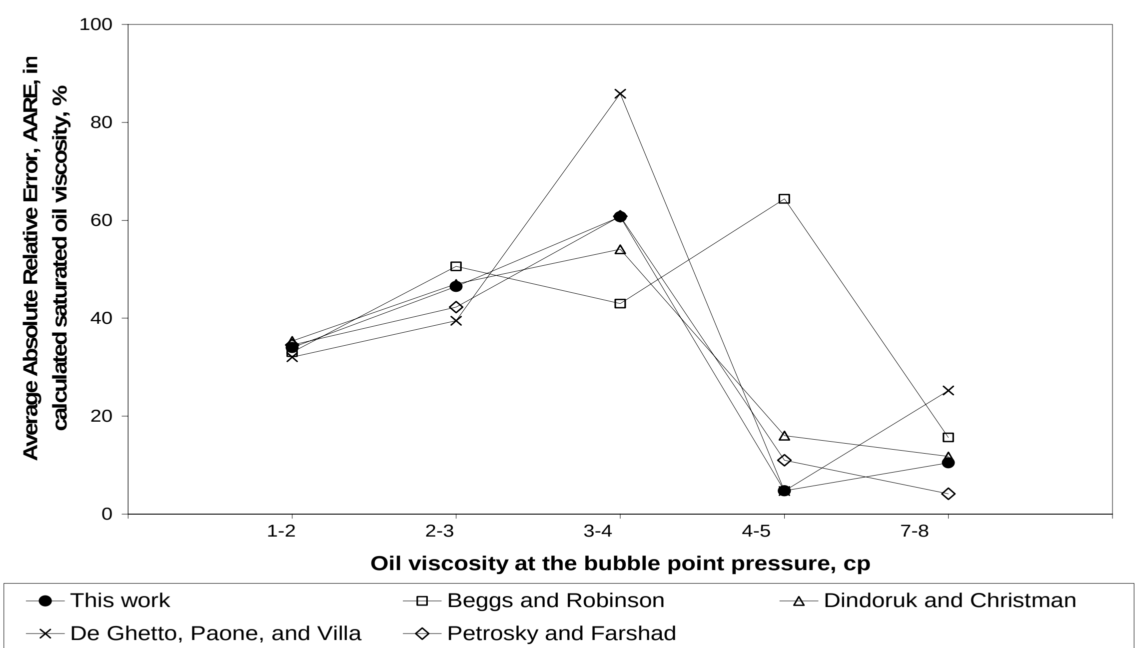

Fig. 52- The reliability of the saturated oil viscosity correlation (regarding AARE) across the range of oil viscosity at the bubble point pressure (1<μ_b≤10cp).

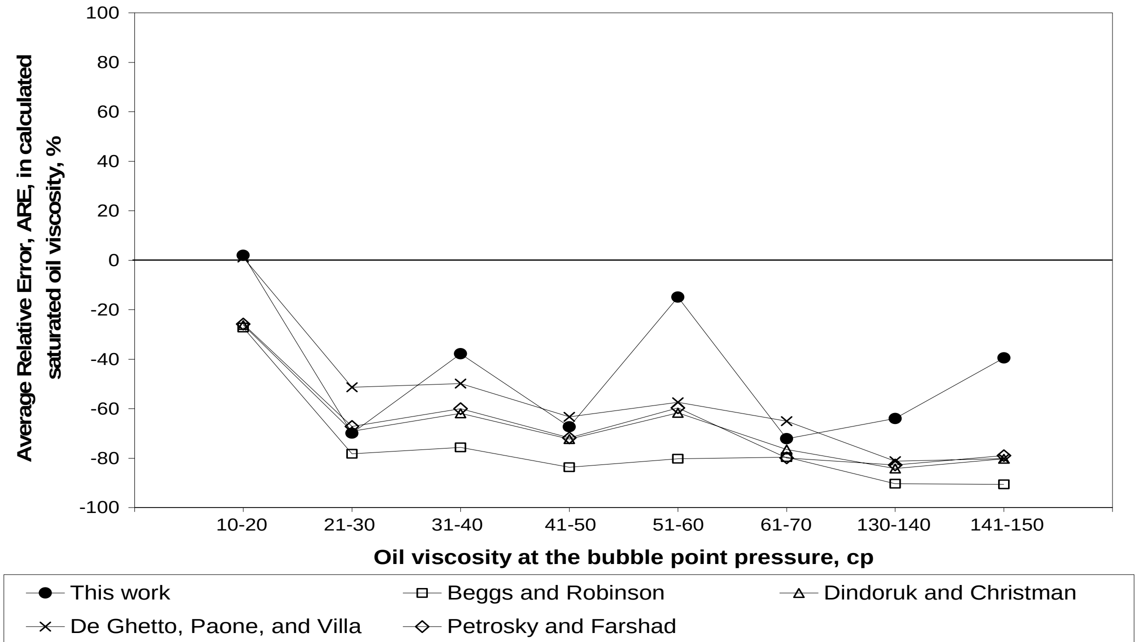

Fig. 53- The reliability of the saturated oil viscosity correlation (regarding ARE) across the range of oil viscosity at the bubble point pressure (μ_b>10cp).

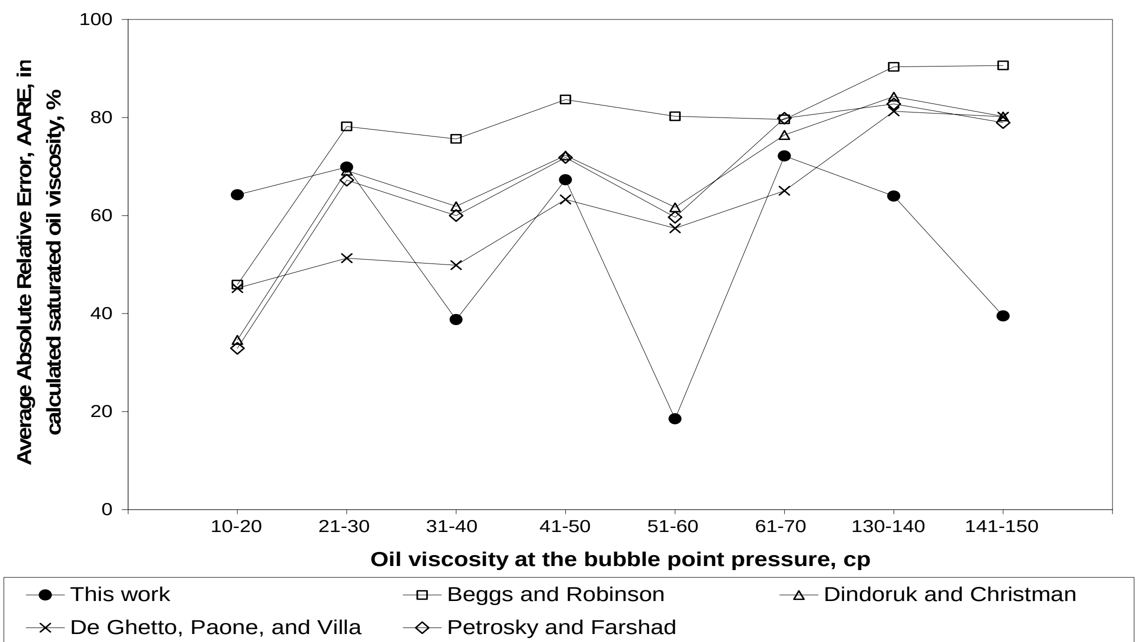

Fig. 54- The reliability of the saturated oil viscosity correlation (regarding AARE) across the range of oil viscosity at the bubble point pressure (μ_b>10cp).

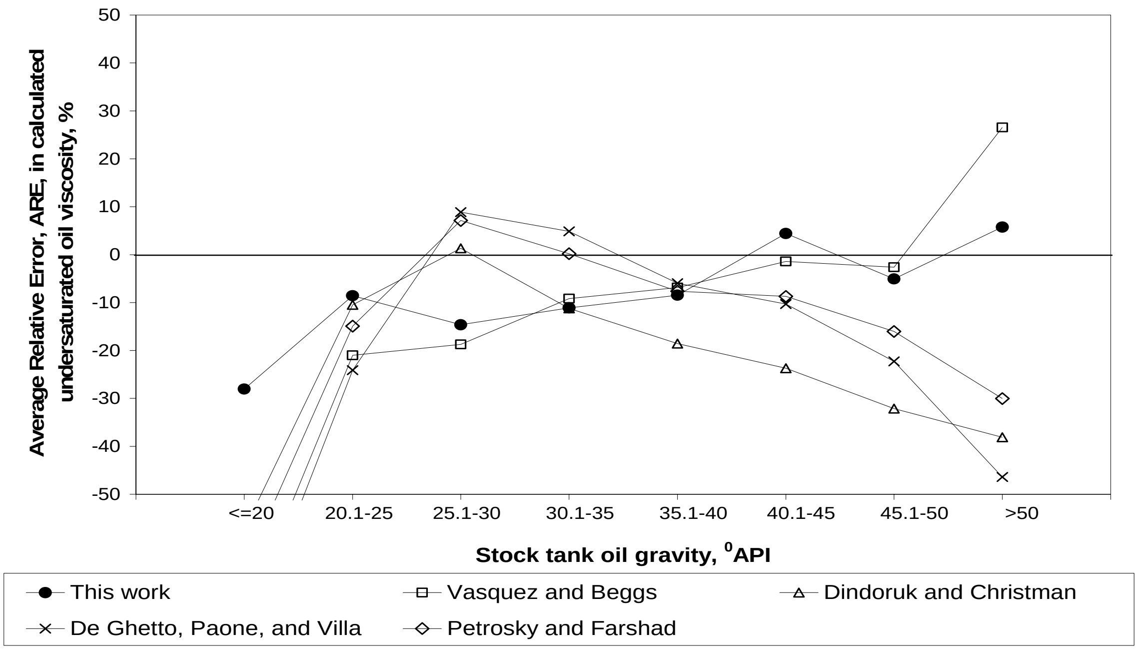

Fig. 55- The reliability of the undersaturated oil viscosity correlation (regarding ARE) across the range of stock-tank oil gravity.

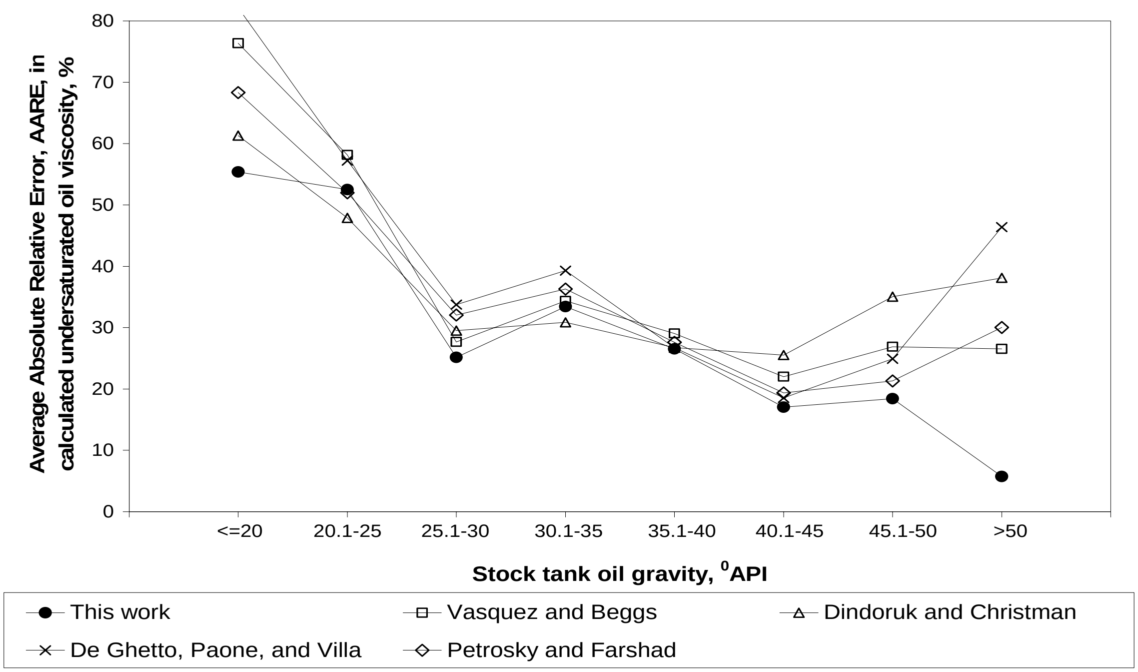

Fig. 56- The reliability of the undersaturated oil viscosity correlation (regarding AARE) across the range of stock-tank oil gravity.

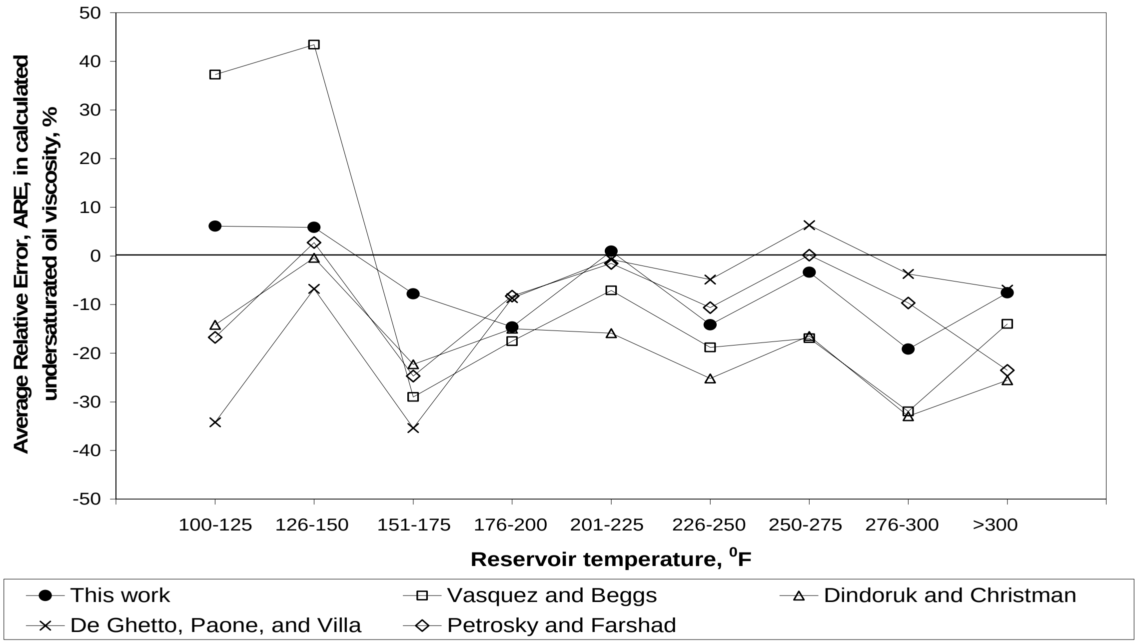

Fig. 57- The reliability of the undersaturated oil viscosity correlation (regarding ARE) across the range of reservoir temperature.

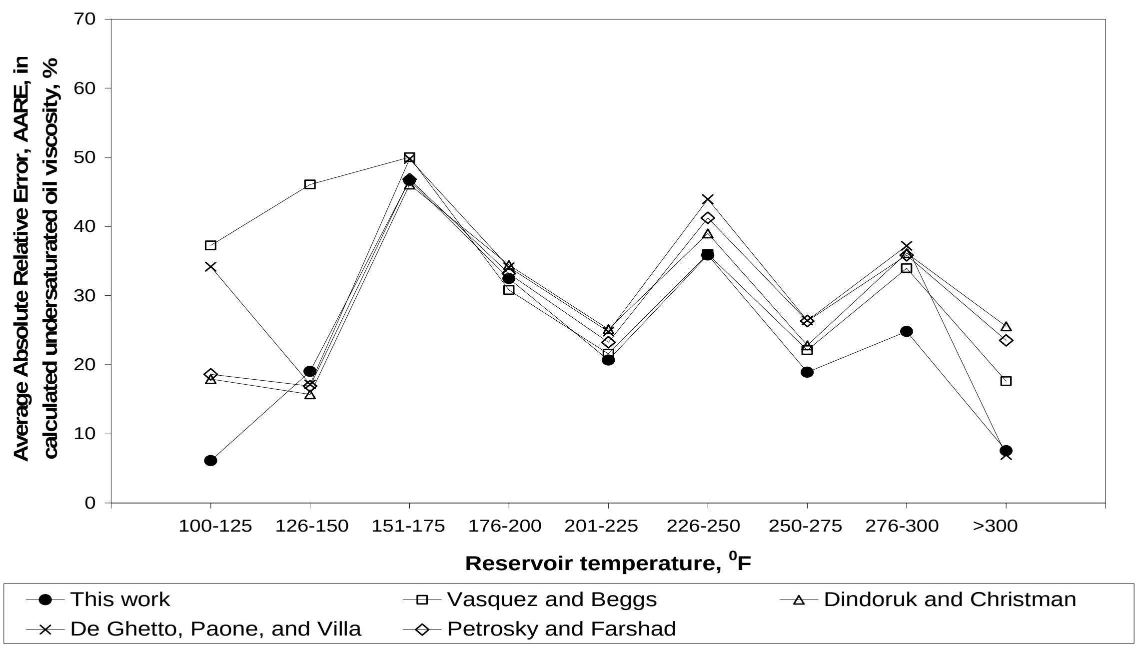

Fig. 58- The reliability of the undersaturated oil viscosity correlation (regarding AARE) across the range of reservoir temperature.

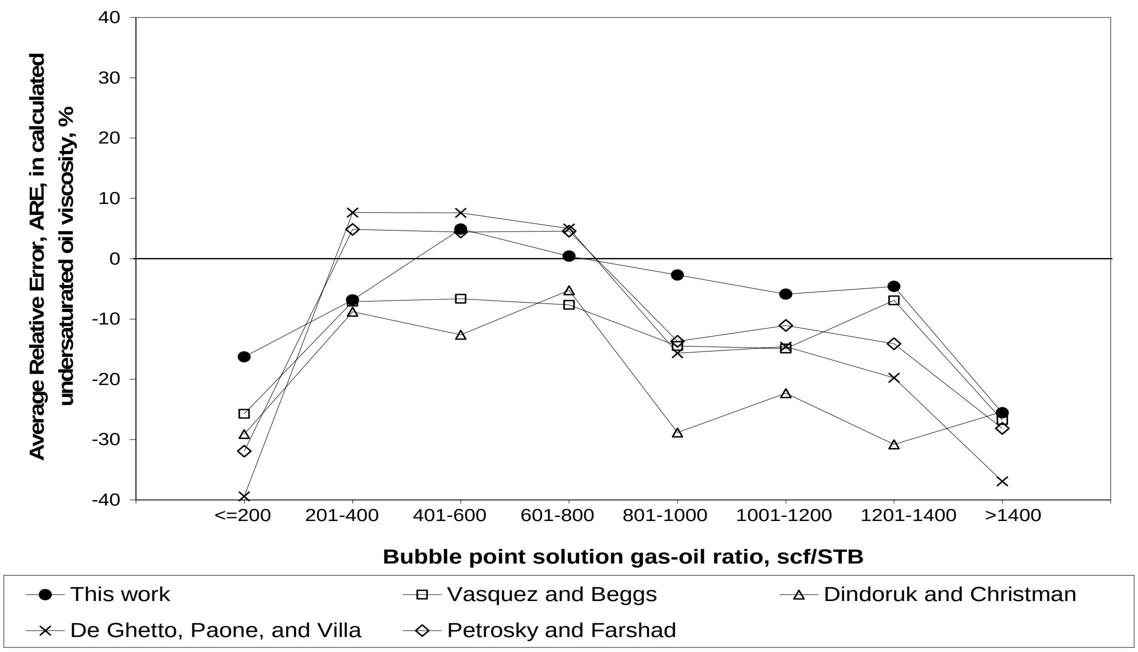

Fig. 59- The reliability of the undersaturated oil viscosity correlation (regarding ARE) across the range of bubble point solution gas-oil ratio.

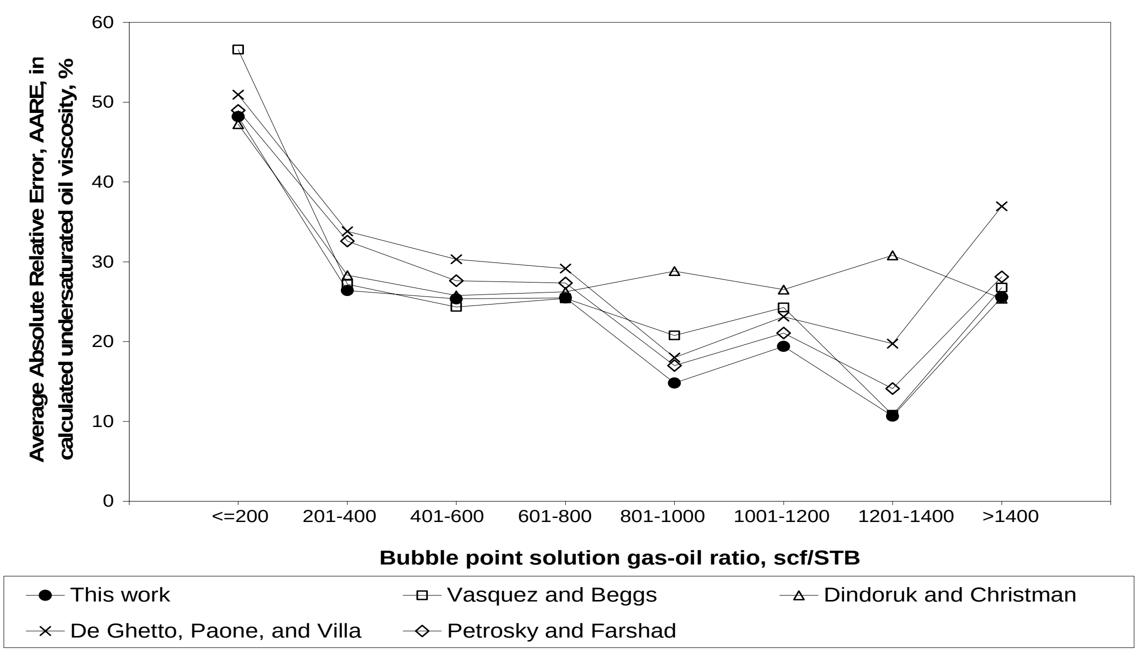

Fig. 60- The reliability of the undersaturated oil viscosity correlation (regarding AARE) across the range of bubble point solution gas-oil ratio.

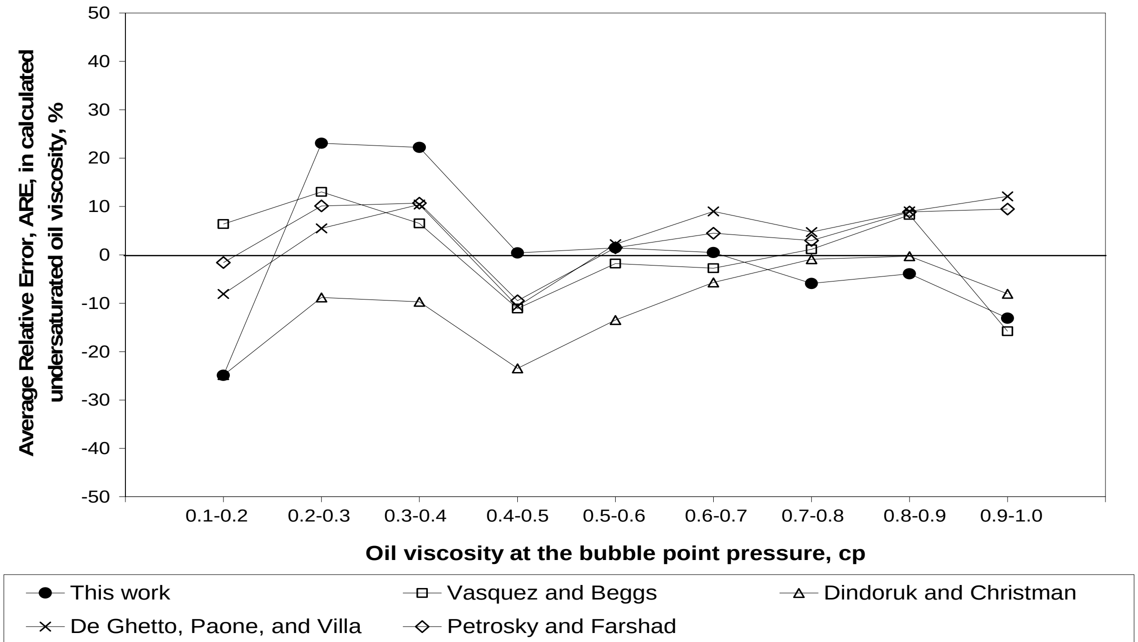

Fig. 61- The reliability of the undersaturated oil viscosity correlation (regarding ARE) across the range of oil viscosity at the bubble point pressure ($\mu_b \leq 1$cp).

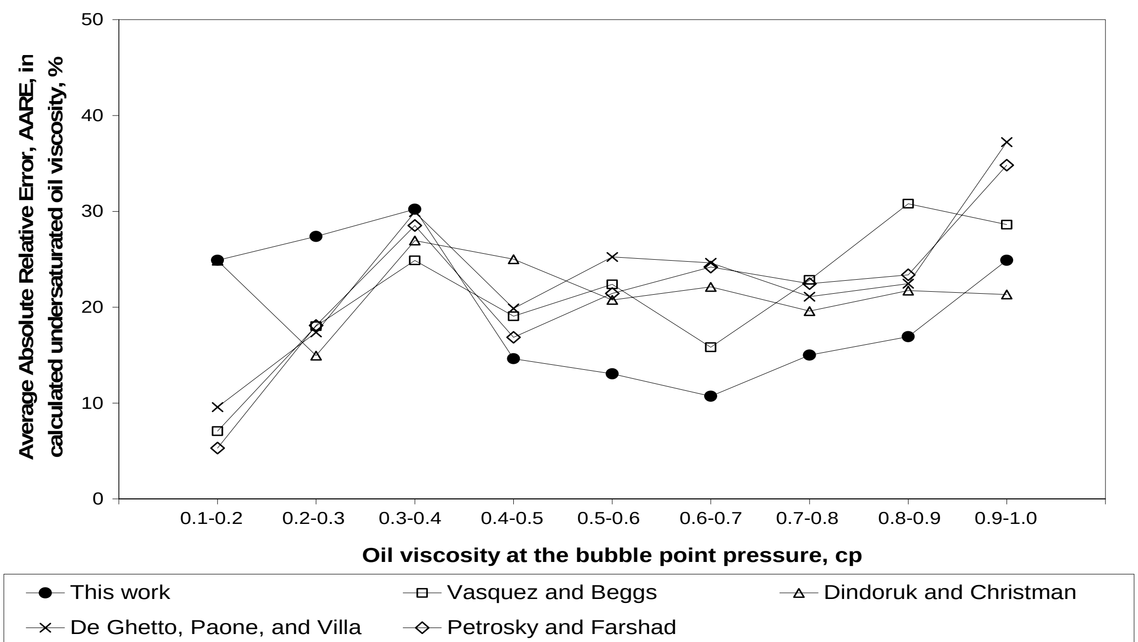

Fig. 62- The reliability of the undersaturated oil viscosity correlation (regarding AARE) across the range of oil viscosity at the bubble point pressure ($\mu_b \leq 1$cp).

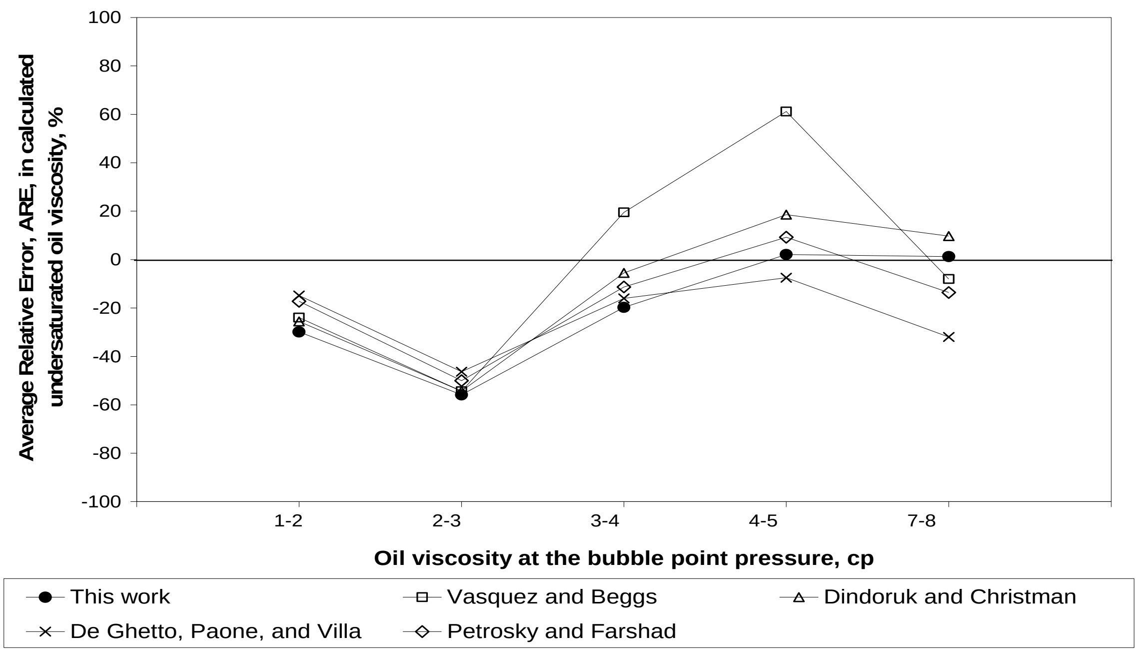

Fig. 63- The reliability of the undersaturated oil viscosity correlation (regarding ARE) across the range of oil viscosity at the bubble point pressure ($1<\mu_b\leq 10$cp).

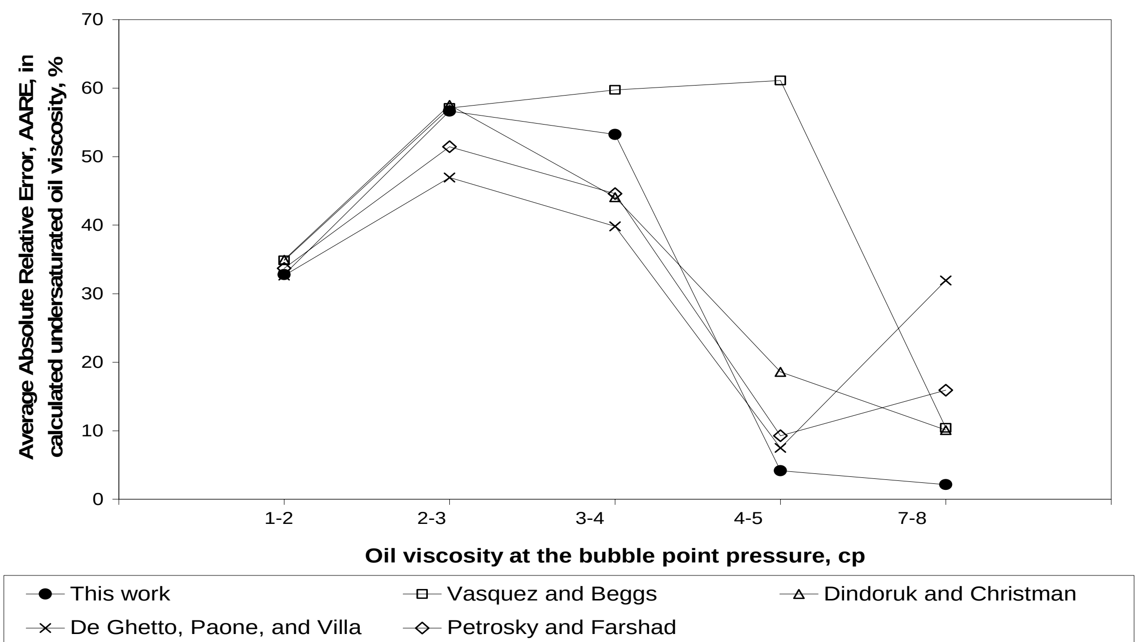

Fig. 64- The reliability of the undersaturated oil viscosity correlation (regarding AARE) across the range of oil viscosity at the bubble point pressure ($1<\mu_b\leq 10$cp).

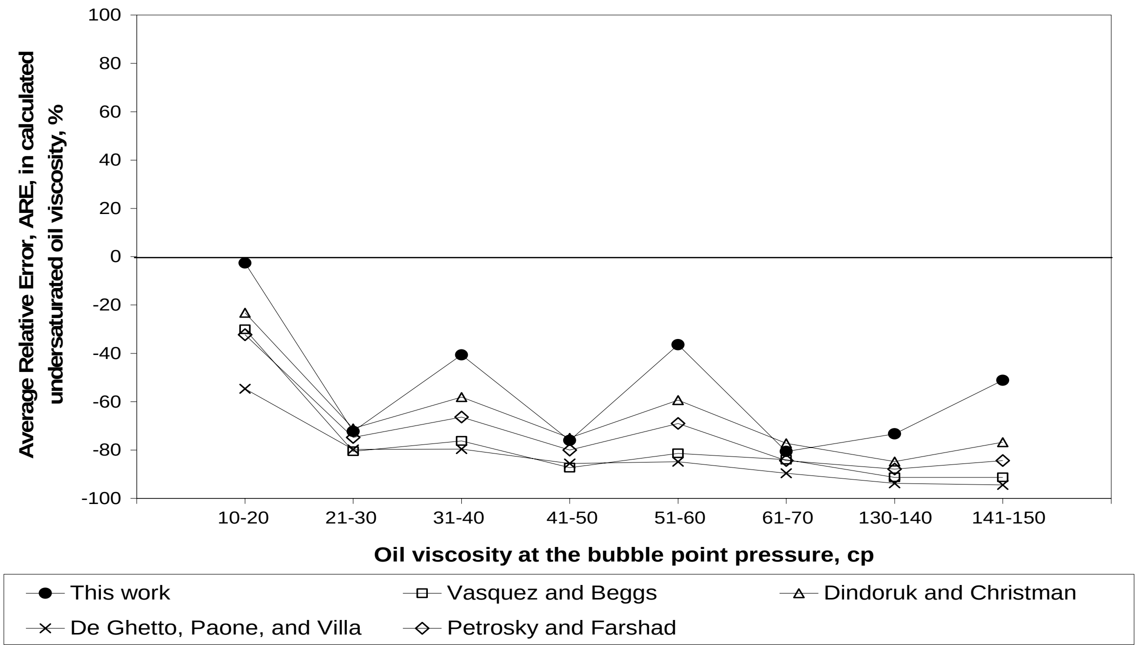

Fig. 65- The reliability of the undersaturated oil viscosity correlation (regarding ARE) across the range of oil viscosity at the bubble point pressure (μ_b>10cp).

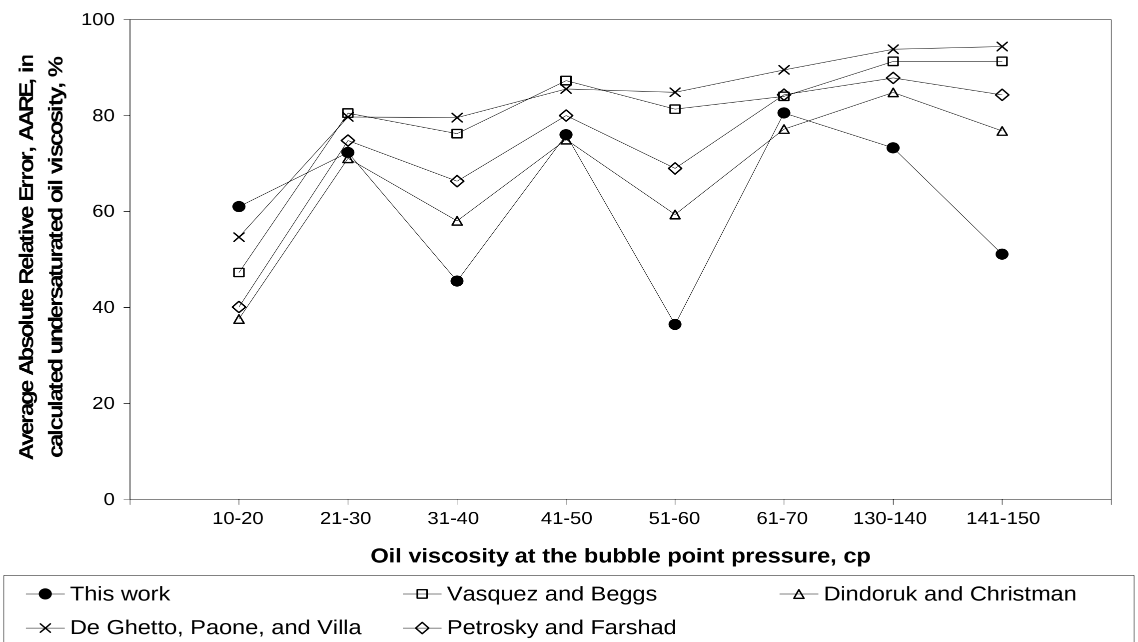

Fig. 66- The reliability of the undersaturated oil viscosity correlation (regarding AARE) across the range of oil viscosity at the bubble point pressure (μ_b>10cp).

CHAPTER X

CONCLUSIONS

The proposed correlation equations for saturated and undersaturated reservoir oil viscosities are created by an effective methodology and achieve the satisfactory performance and reliability. The following can be concluded:

- A large database used in this research study covers a wide range of fluid properties for black oil and is carefully inspected the overall quality before correlating the proposed oil viscosity equations.
- The Beggs and Robinson correlation equation[4] for saturated oil viscosity and the Petrosky and Farshad correlation equation[23] for undersaturated oil viscosity are the most reliable correlation equations among published correlation equations.
- Using only an oil density at the bubble point pressure, as shown in the Abu-Khamsin and Al-Marhoun[18] and the Hanafy *et al.*[25] correlation equations, is not enough to correlate the high performance reservoir oil viscosity equations.
- Based on the results of the effective methodology, reservoir oil density is the most influential parameter for correlating both saturated and undersaturated oil viscosity models.
- Using the combination of the reservoir oil density and other field-measured parameters for correlating the oil viscosity equations does not quite improve the performance of the proposed correlation equations.
- The proposed strategy for correlating oil viscosity equations is very effective and is derived from the true relationship between the dependent and independent variables.

- The proposed correlation equations for saturated oil viscosity, **Eq. 77** and **Eq. 78**, and undersaturated oil viscosity, **Eq. 83** through **Eq. 85**, provide a reasonable prediction of reservoir oil viscosity.
- No matter how much error is in the calculated bubble point oil viscosity, the proposed undersaturated oil viscosity correlation equation always provides the best prediction of all published correlation equations.
- At any reservoir conditions, the proposed saturated and undersaturated oil viscosity correlation equations have higher performance and validity than all published correlation equations.
- The proposed correlation equations work very effective within the ranges of fluid properties provided in the database.
- Errors in laboratory-measured oil viscosity cause the deficiency in the proposed oil viscosity correlation equations, which results in the high value of AARE. These expected errors cannot be corrected and are unavoidable from routine laboratory measurement of oil viscosity.

NOMENCLATURE

a	=	exponent in the proposed undersaturated oil viscosity correlation
API	=	stock-tank oil gravity in ^{o}API
A, B	=	constants in various saturated oil viscosity correlations
B_o	=	oil formation volume factor in res bbl/STB
c_o	=	liquid coefficient of isothermal compressibility in psia^{-1}
C	=	constant in the Beggs and Robinson correlation
D	=	constant in the Standing correlation
E	=	constant in the Vasquez and Beggs correlation
f_0	=	optimal transformations for dependent variable
f_0^{-1}	=	inverse of optimal transformations for dependent variable
$f_1, f_2, \ldots$	=	optimal transformations for independent variables
F	=	constant in the Al-Khafaji, Abdul-Majeed, and Hassoon correlation
G	=	constant in the Abdul-Majeed, Kattan, and Salman correlation
H, I	=	constants in the Kartoatmodjo and Schmidt correlation
J, K	=	constants in the Petrosky and Farshad correlation
L	=	constant in the Almehaideb correlation
M	=	constant in the Elsharkawy and Gharbi correlation
N	=	total number of data points
O	=	constant in the Dindoruk and Christman correlation
p	=	reservoir pressure in psia
p_b	=	bubble point pressure in psia
p_{b_tr}	=	transformed bubble point pressure
r	=	residual
R_S	=	solution gas-oil ratio in scf/STB
R_{Sb}	=	solution gas-oil ratio at bubble point pressure in scf/STB
R^2	=	correlation R^2 value
T	=	reservoir temperature in ^{o}F

T_p = pour point temperature in ^oF

V_b = volume of liquid at the bubble point in bbl

V_t = total volume in bbl

$\left(\frac{V_t}{V_b}\right)_F$ = relative total volume (oil and gas) by flash vaporization

$x_1, x_2, \ldots$ = independent variables

y = dependent variable

y^{pre} = predicted dependent variable

z_0 = transformed dependent variable

$z_1, z_2, \ldots$ = transformed independent variables

z_n^*, z_{tr} = summation of transformed independent variables

Greek

γ_o = oil specific gravity

γ_g = gas specific gravity

μ_{calc} = calculated oil viscosity (dynamic) in cp

μ_{meas} = measured oil viscosity (dynamic) in cp

μ_o = oil viscosity (dynamic) in cp

μ_{ob} = oil viscosity (dynamic) at bubble point pressure in cp

μ_{od} = oil viscosity (dynamic) at atmospheric pressure (dead oil) in cp

μ_{o_tr} = transformed reservoir oil viscosity

ρ_a = apparent liquid density in lb/cu ft

ρ_{bs} = liquid density at reservoir pressure and 60^oF in lb/cu ft

ρ_o = reservoir oil density in lb/cu ft

ρ_{o_tr} = transformed reservoir oil density

ρ_{ob} = reservoir oil density at bubble point pressure in lb/cu ft

ρ_{ob_tr} = transformed reservoir oil density at bubble point pressure

ρ_{po} = density of pseudoliquid in lb/cu ft

ρ_{sto} = stock-tank oil density in lb/cu ft

ρ_{sto_tr} = transformed stock-tank oil density

ρ_w = density of water (brine) in lb/cu ft

Subscripts

calc = calculation

meas = measurement

g = gas

i = different value of data points

j = different stage independent variables

k = total stage independent variables

m = total number of independent variable

n = different independent variables

o = oil

ob = oil at the bubble point pressure

_tr = transformed value

Abbreviation

PVT = pressure-volume-temperature

ACE = alternating conditional expectation

GRACE = graphical alternating conditional expectation

ARE = average relative error

AARE = average absolute relative error

ARA = average relative adjustment

AARA = average absolute relative adjustment

SD = standard deviation

UAE = United Arab Emirates

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APPENDIX A

PERFORMANCE OF VISCOSITY CORRELATION EQUATIONS FOR SATURATED RESERVOIR OIL (183 PVT REPORTS/ 1118 DATA POINTS)

The proposed correlation for saturated oil viscosity

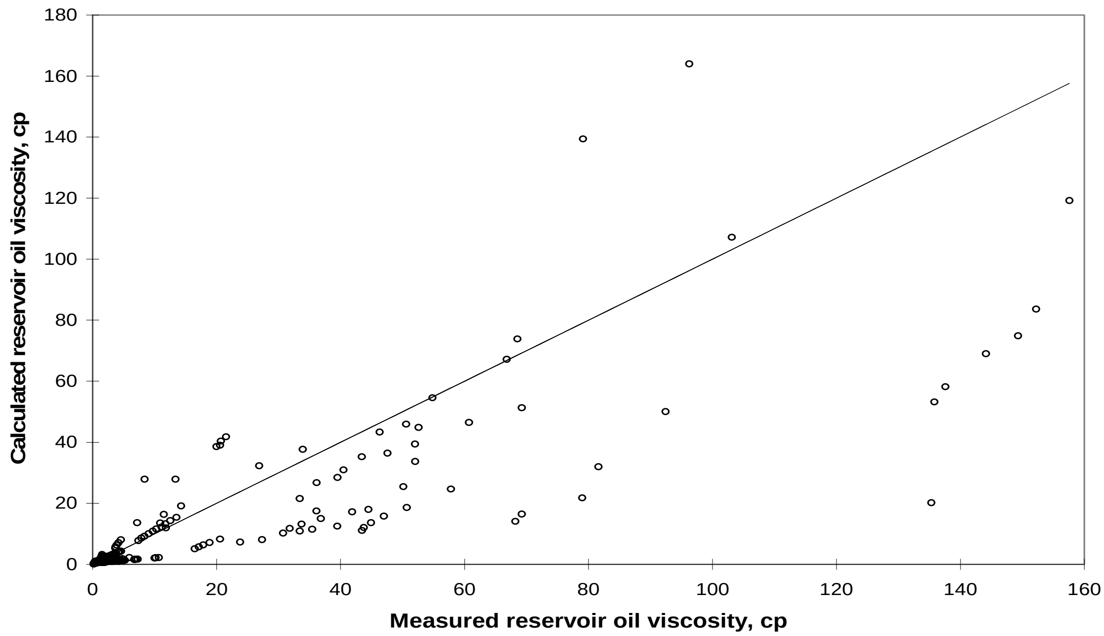

Fig. A.1- Graphical interpretation of the proposed correlation for saturated oil viscosity on Cartesian coordinates.

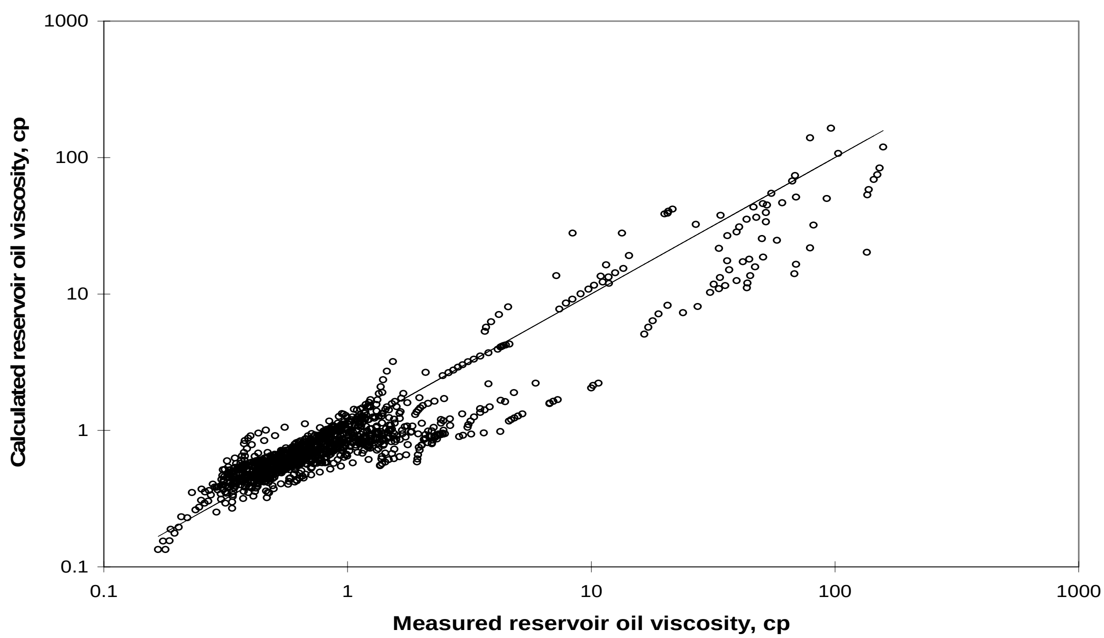

Fig. A.2- Graphical interpretation of the proposed correlation for saturated oil viscosity on logarithmic coordinates.

The Beggs and Robinson correlation for saturated oil viscosity

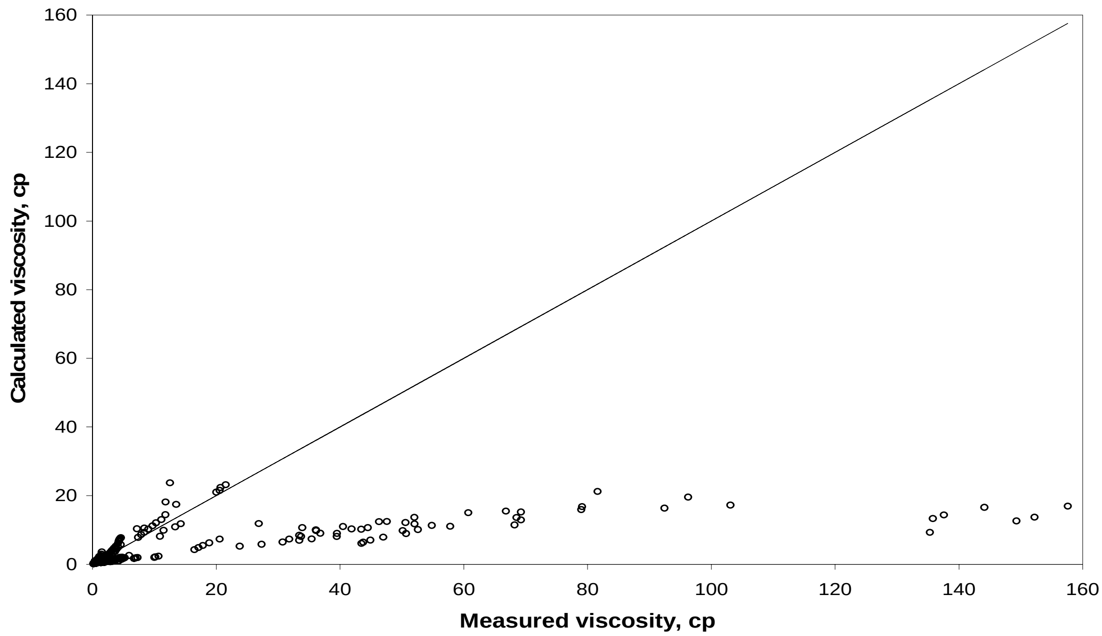

Fig. A.3- Graphical interpretation of the Beggs and Robinson correlation for saturated oil viscosity on Cartesian coordinates.

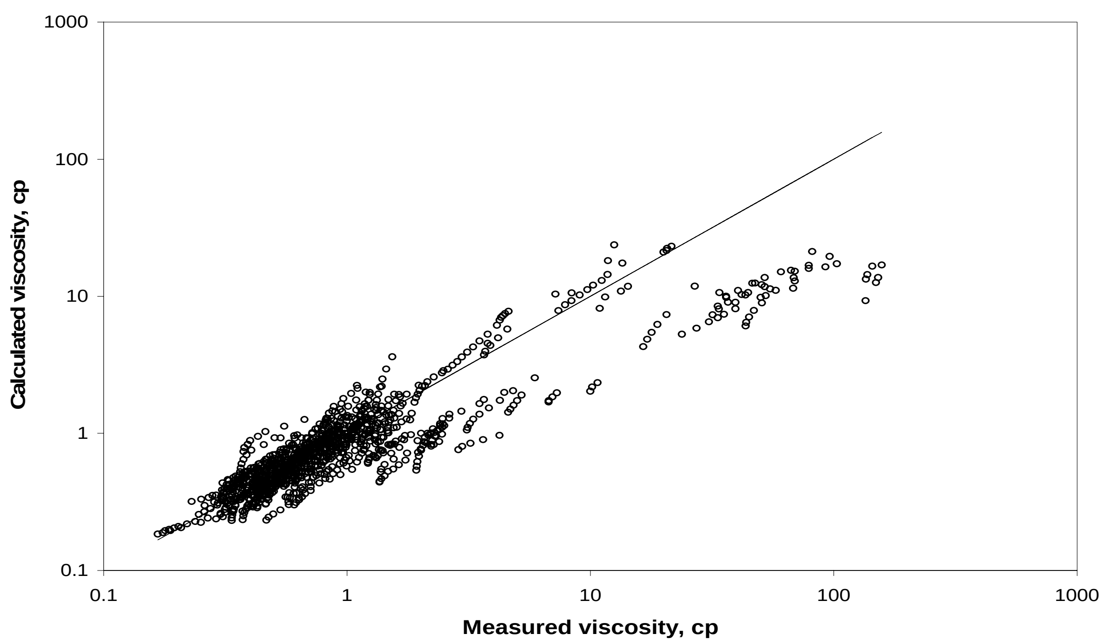

Fig. A.4- Graphical interpretation of the Beggs and Robinson correlation for saturated oil viscosity on logarithmic coordinates.

The De Ghetto, Paone, and Villa correlation for saturated oil viscosity

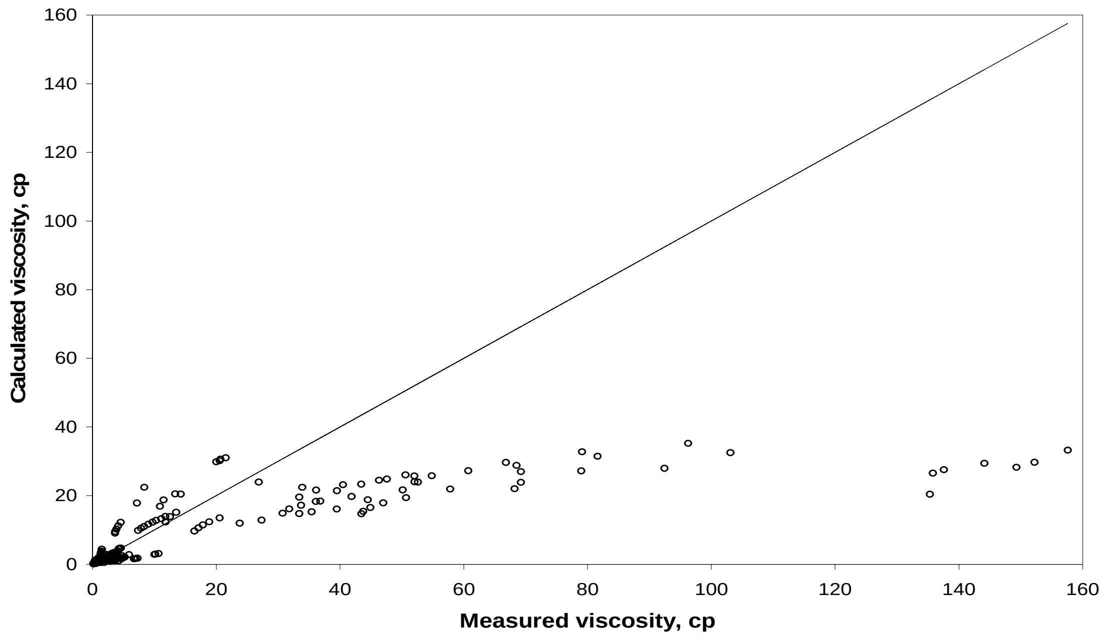

Fig. A.5- Graphical interpretation of the De Ghetto, Paone, and Villa correlation for saturated oil viscosity on Cartesian coordinates.

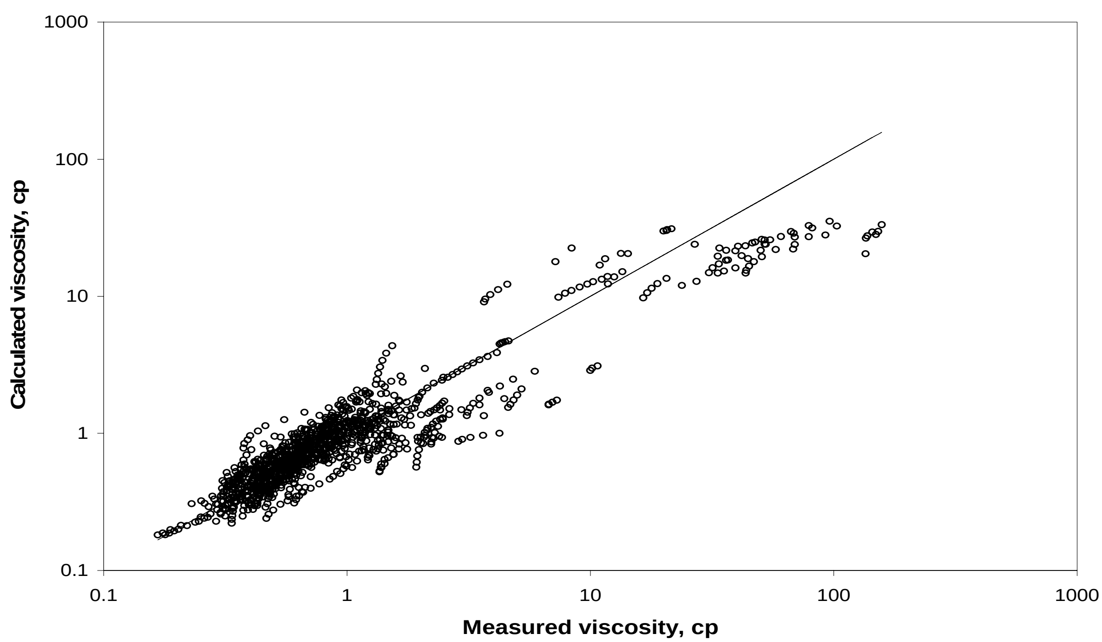

Fig. A.6- Graphical interpretation of the De Ghetto, Paone, and Villa correlation for saturated oil viscosity on logarithmic coordinates.

The Dindoruk and Christman correlation for saturated oil viscosity

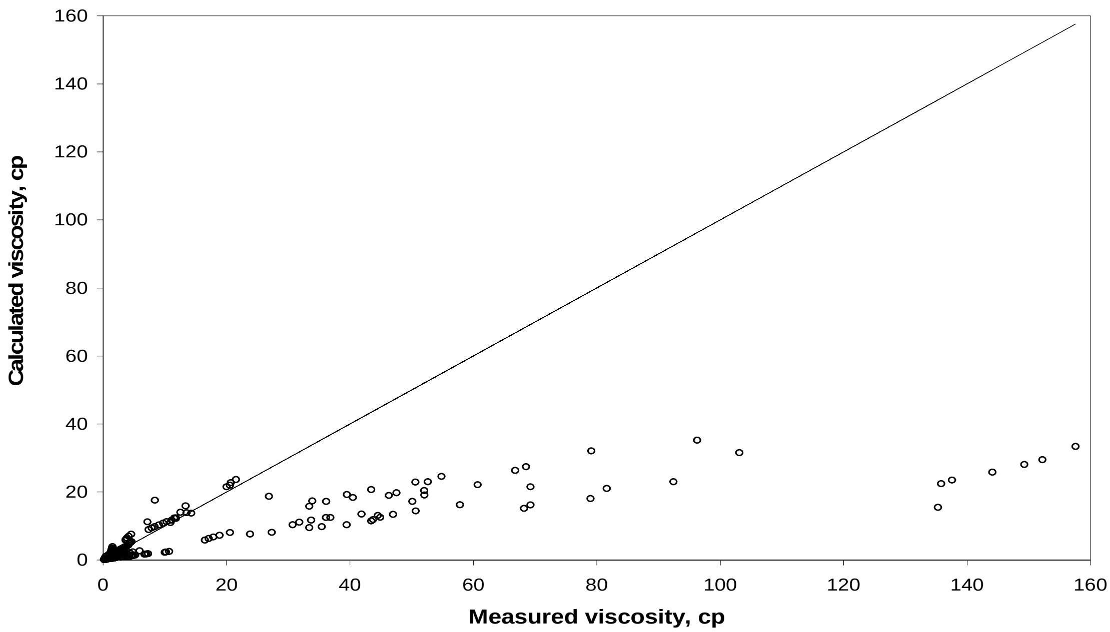

Fig. A.7- Graphical interpretation of the Dindoruk and Christman correlation for saturated oil viscosity on Cartesian coordinates.

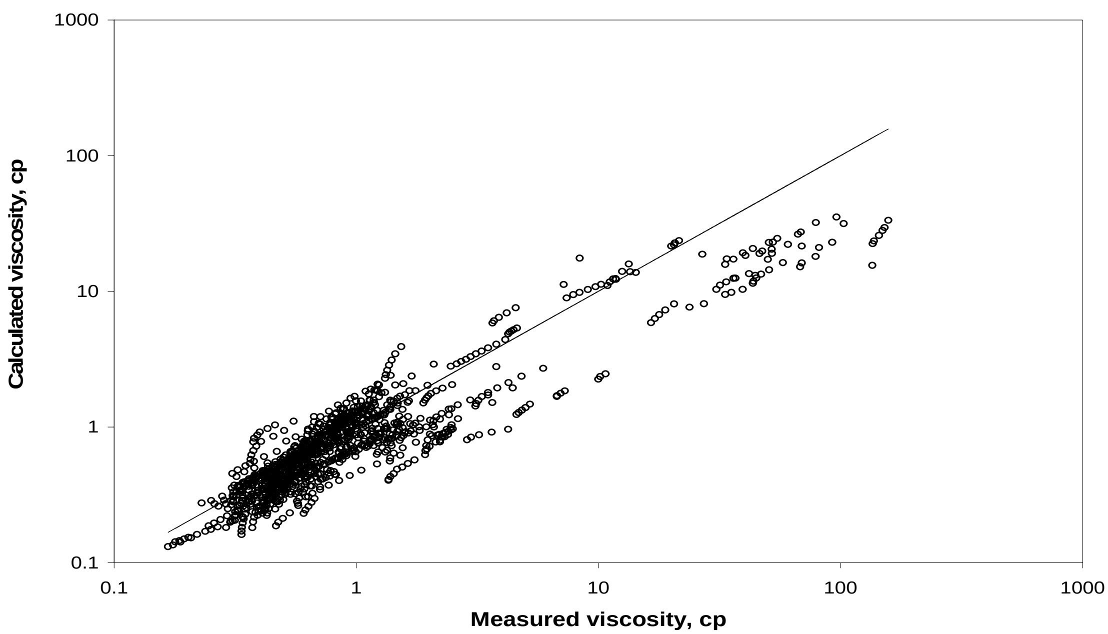

Fig. A.8- Graphical interpretation of the Dindoruk and Christman correlation for saturated oil viscosity on logarithmic coordinates.

The McCain correlation for saturated oil viscosity

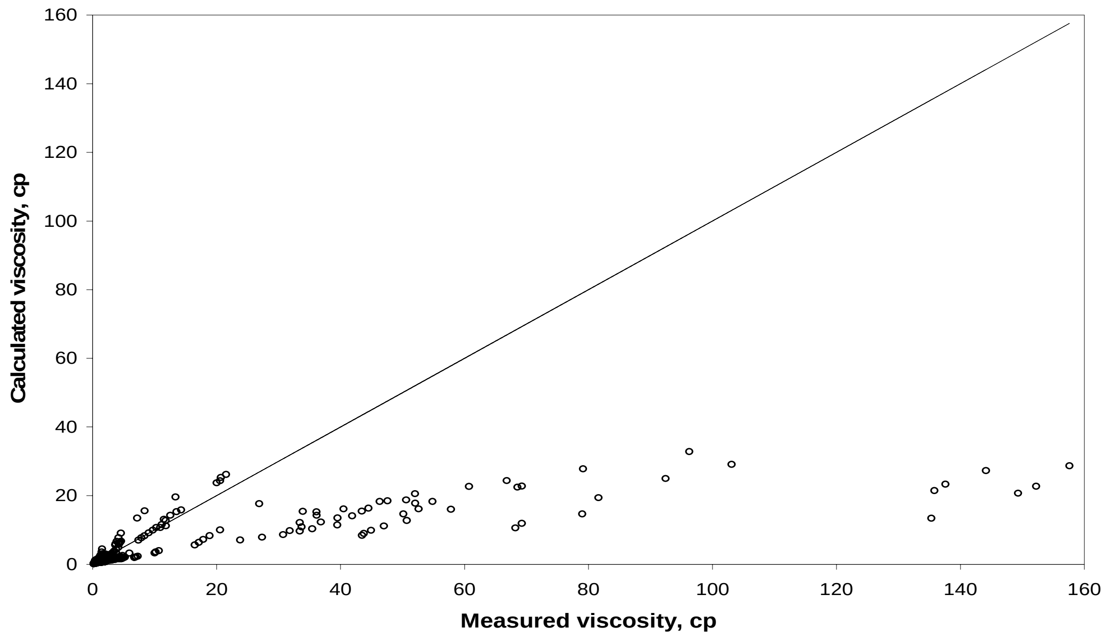

Fig. A.9- Graphical interpretation of the McCain correlation for saturated oil viscosity on Cartesian coordinates.

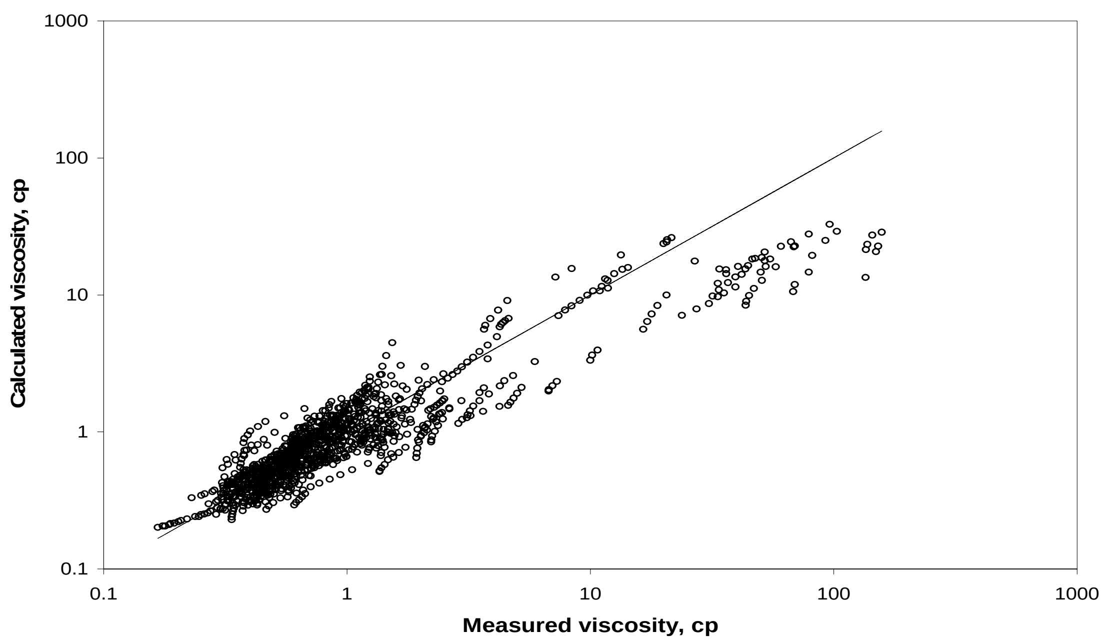

Fig. A.10- Graphical interpretation of the McCain correlation for saturated oil viscosity on logarithmic coordinates.

The Almehaideb correlation for saturated oil viscosity

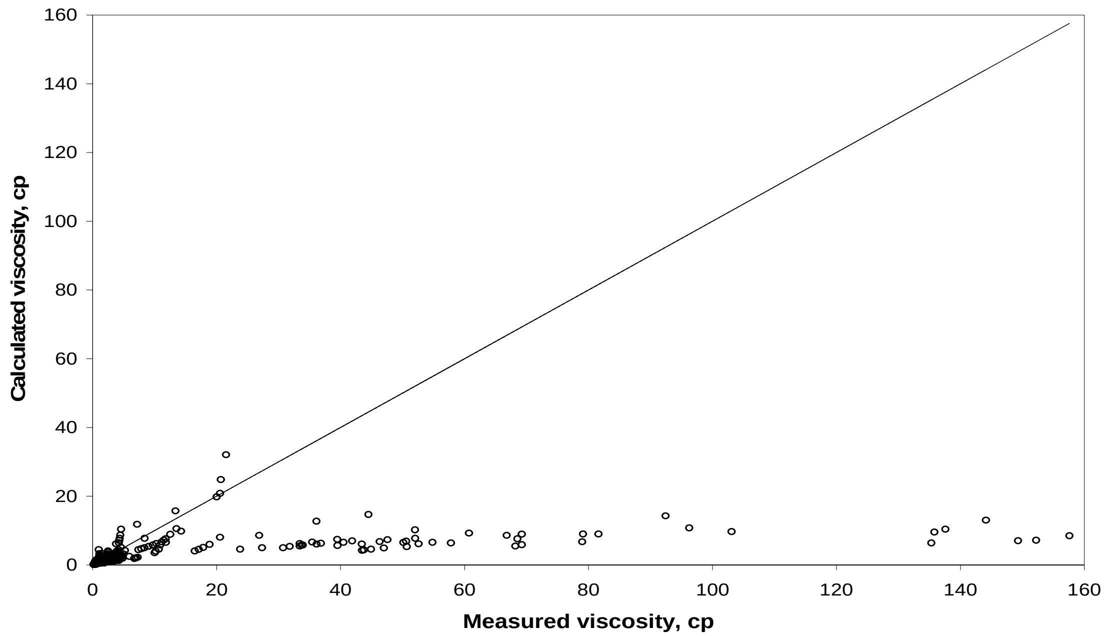

Fig. A.11- Graphical interpretation of the Almehaideb correlation for saturated oil viscosity on Cartesian coordinates.

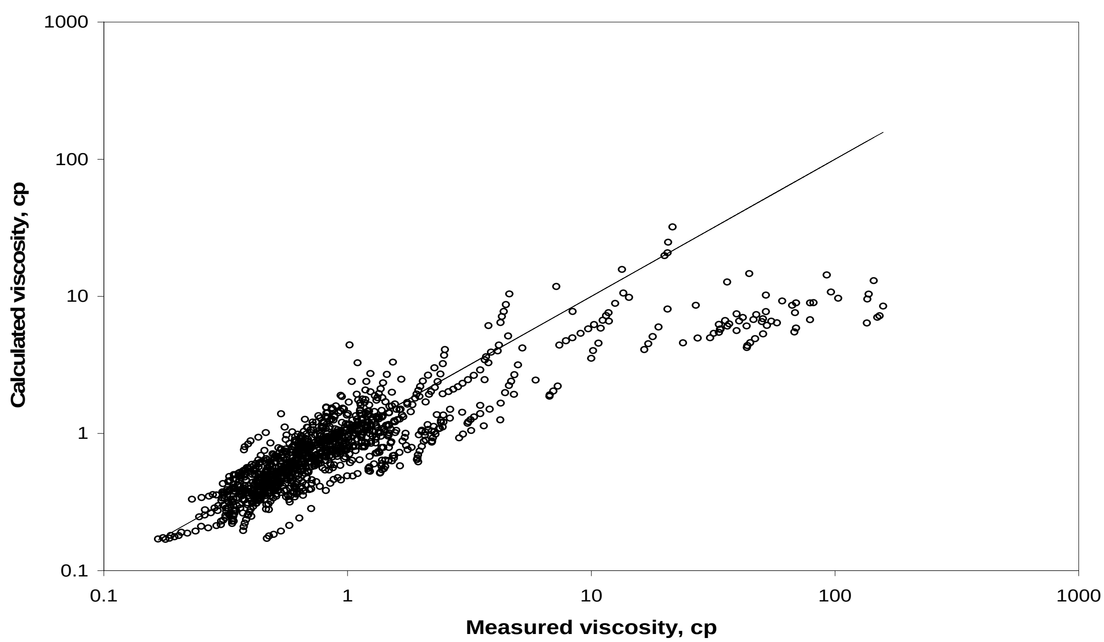

Fig. A.12- Graphical interpretation of the Almehaideb correlation for saturated oil viscosity on logarithmic coordinates.

The Petrosky and Farshad correlation for saturated oil viscosity

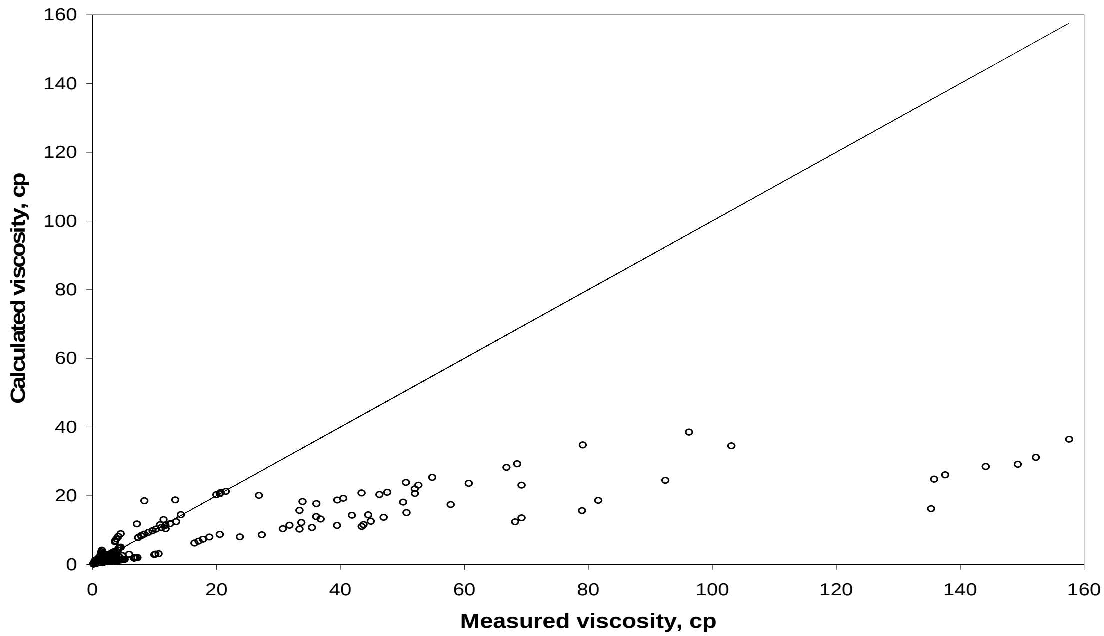

Fig. A.13- Graphical interpretation of the Petrosky and Farshad correlation for saturated oil viscosity on Cartesian coordinates.

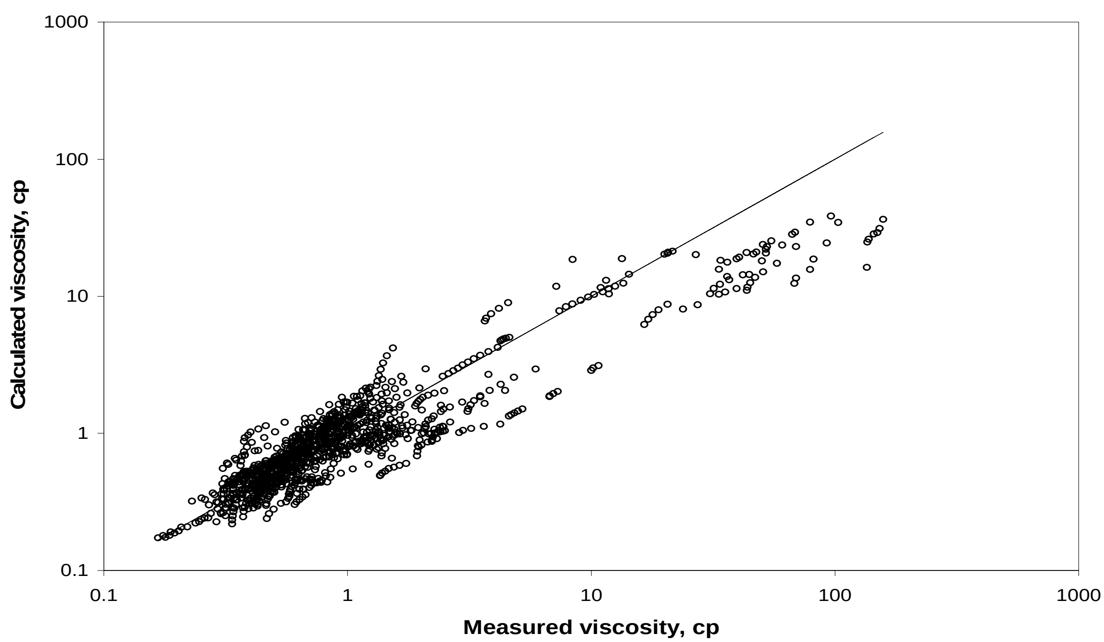

Fig. A.14- Graphical interpretation of the Petrosky and Farshad correlation for saturated oil viscosity on logarithmic coordinates.

The Standing correlation for saturated oil viscosity

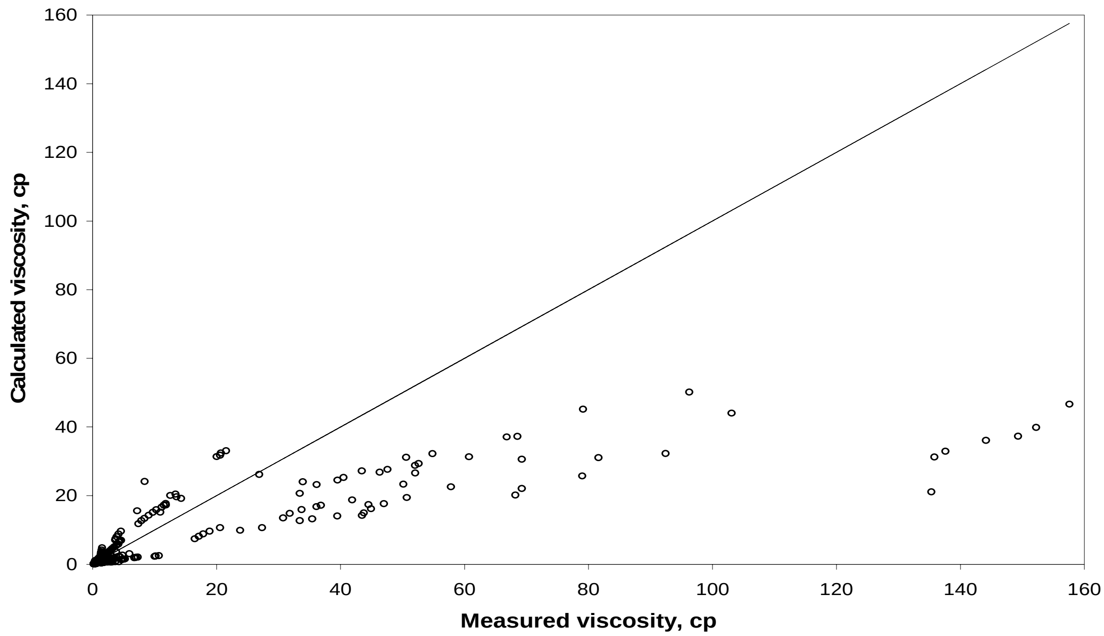

Fig. A.15- Graphical interpretation of the Standing correlation for saturated oil viscosity on Cartesian coordinates.

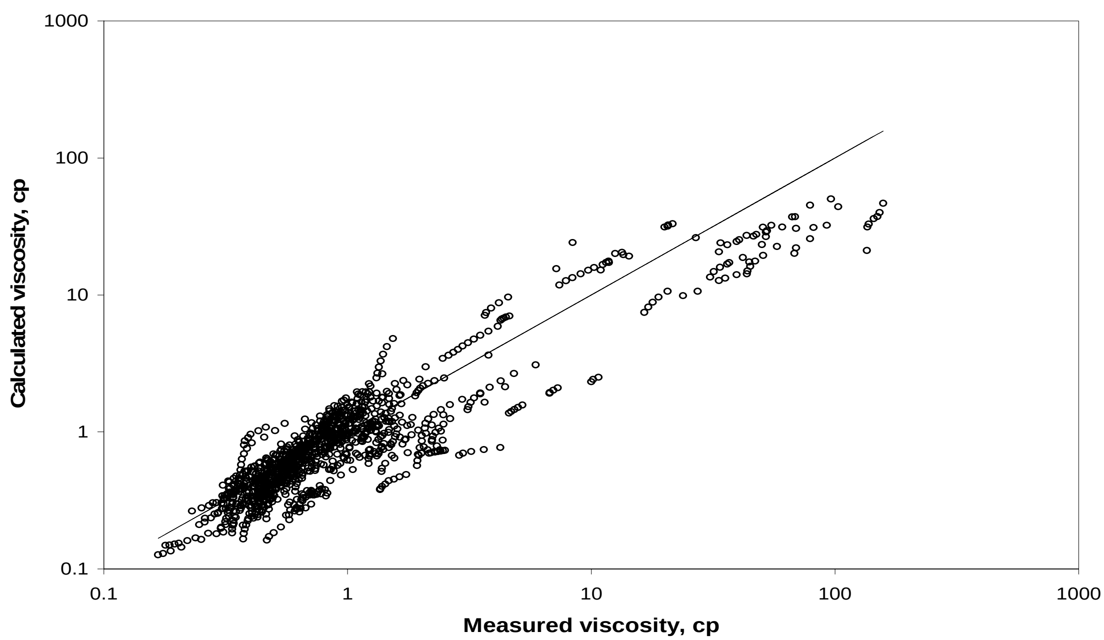

Fig. A.16- Graphical interpretation of the Standing correlation for saturated oil viscosity on logarithmic coordinates.

The Elsharkawy and Gharbi correlation for saturated oil viscosity

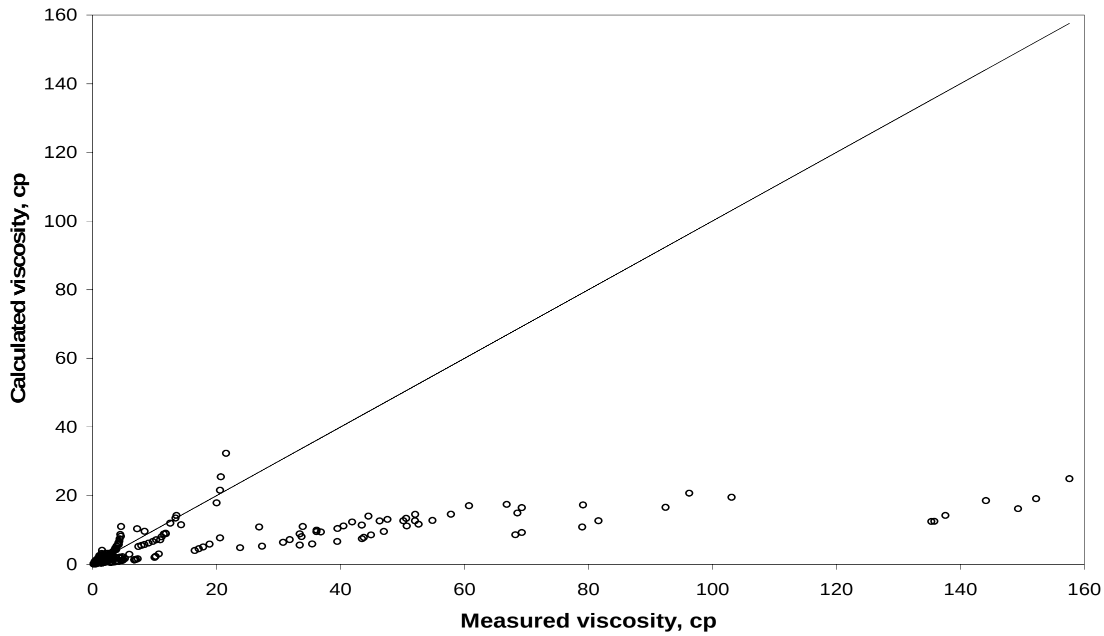

Fig. A.17- Graphical interpretation of the Elsharkawy and Gharbi correlation for saturated oil viscosity on Cartesian coordinates.

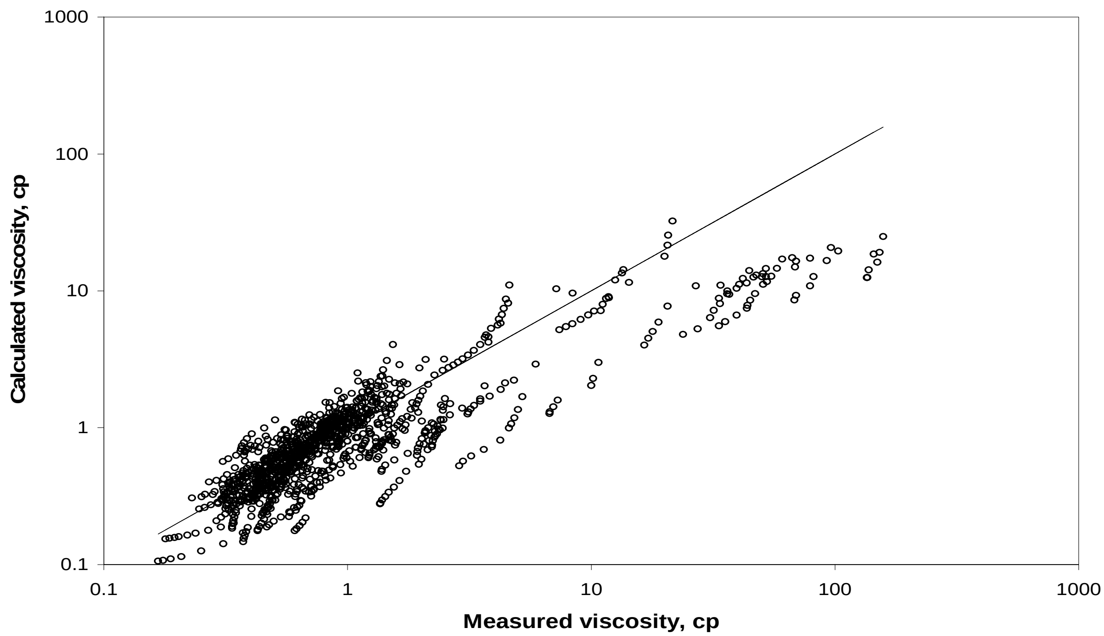

Fig. A.18- Graphical interpretation of the Elsharkawy and Gharbi correlation for saturated oil viscosity on logarithmic coordinates.

The Al-Khafaji, Abdul-Majeed, and Hassoon correlation for saturated oil viscosity

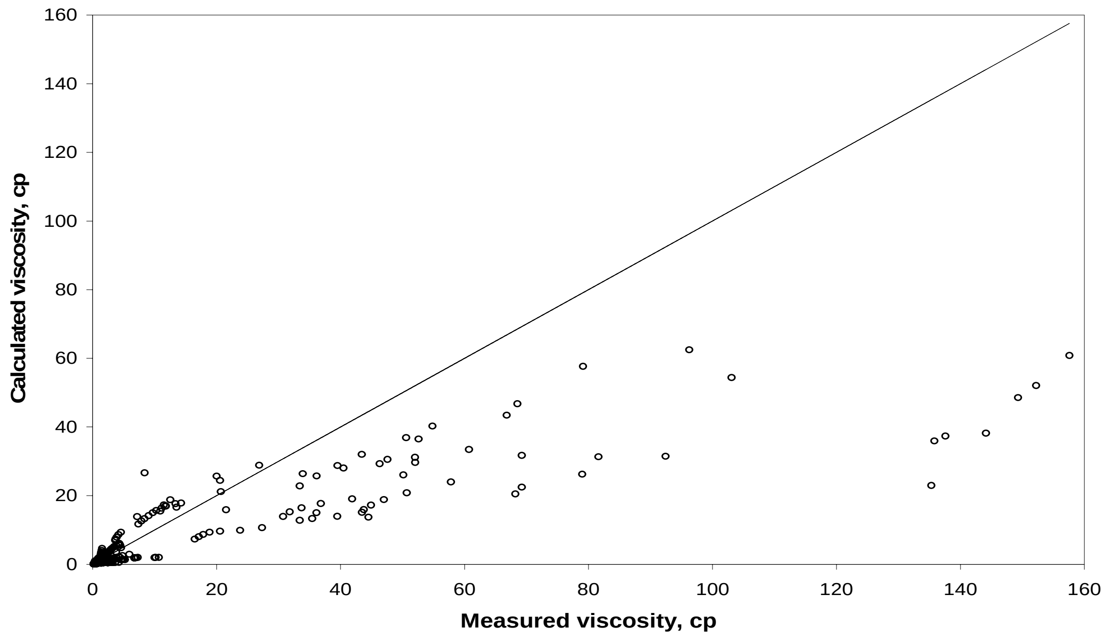

Fig. A.19- Graphical interpretation of the Al-Khafaji, Abdul-Majeed, and Hassoon correlation for saturated oil viscosity on Cartesian coordinates.

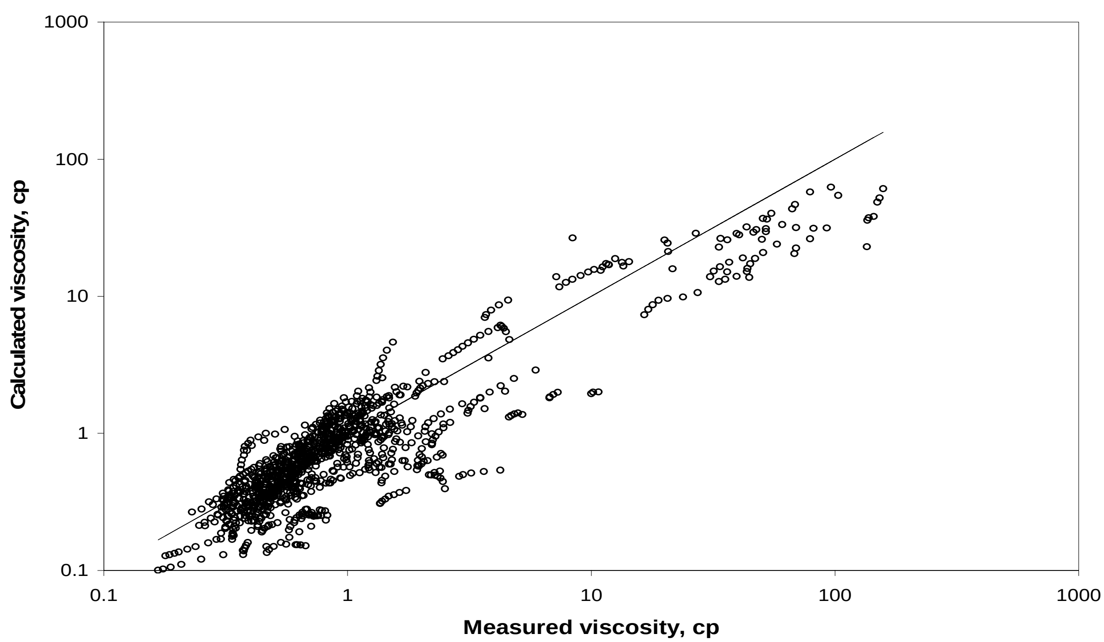

Fig. A.20- Graphical interpretation of the Al-Khafaji, Abdul-Majeed, and Hassoon correlation for saturated oil viscosity on logarithmic coordinates.

The Kartoatmodjo and Schmidt correlation for saturated oil viscosity

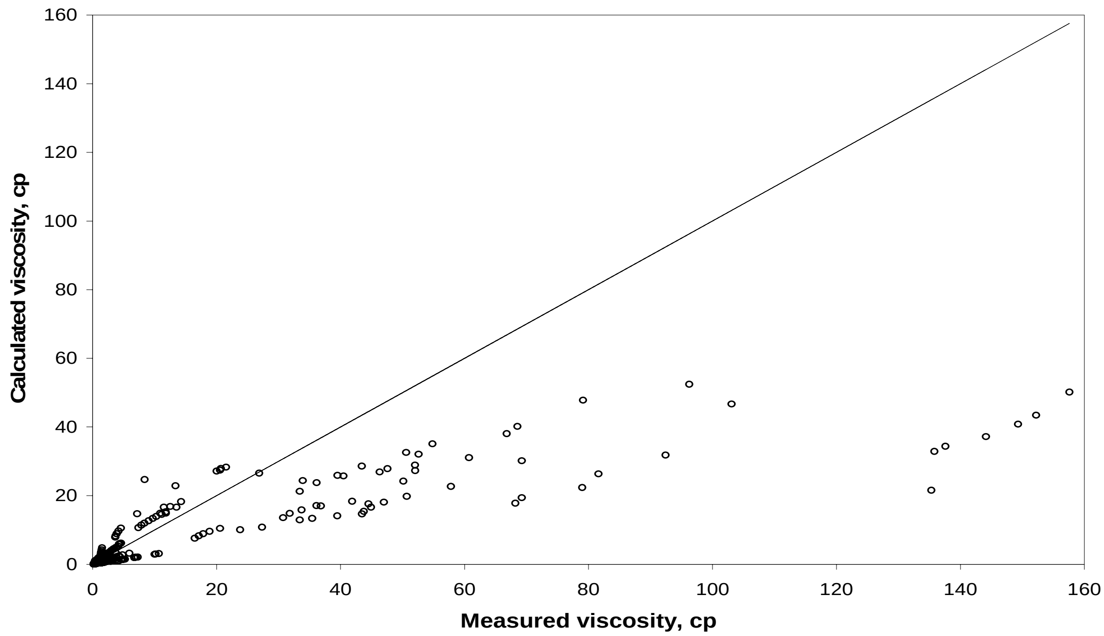

Fig. A.21- Graphical interpretation of the Kartoatmodjo and Schmidt correlation for saturated oil viscosity on Cartesian coordinates.

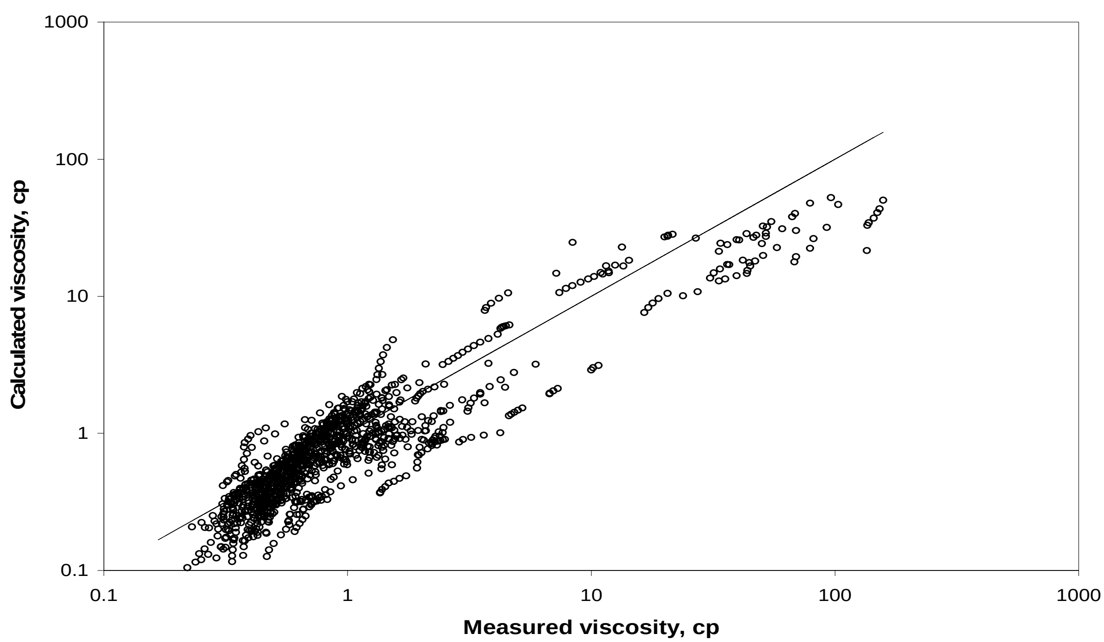

Fig. A.22- Graphical interpretation of the Kartoatmodjo and Schmidt correlation for saturated oil viscosity on logarithmic coordinates.

The Bergman correlation for saturated oil viscosity

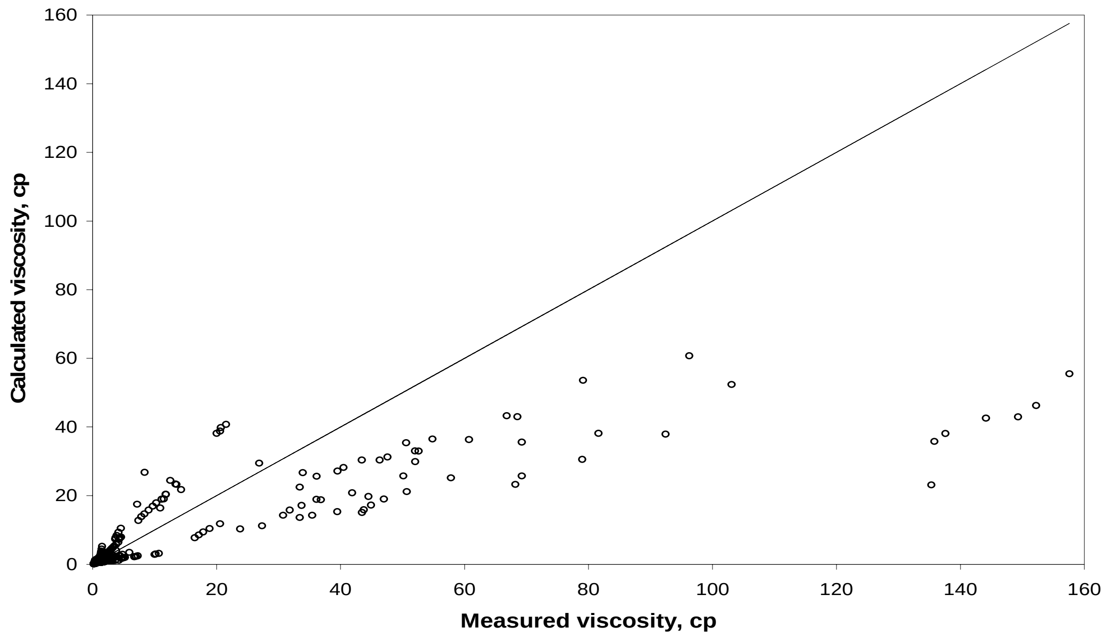

Fig. A.23- Graphical interpretation of the Bergman correlation for saturated oil viscosity on Cartesian coordinates.

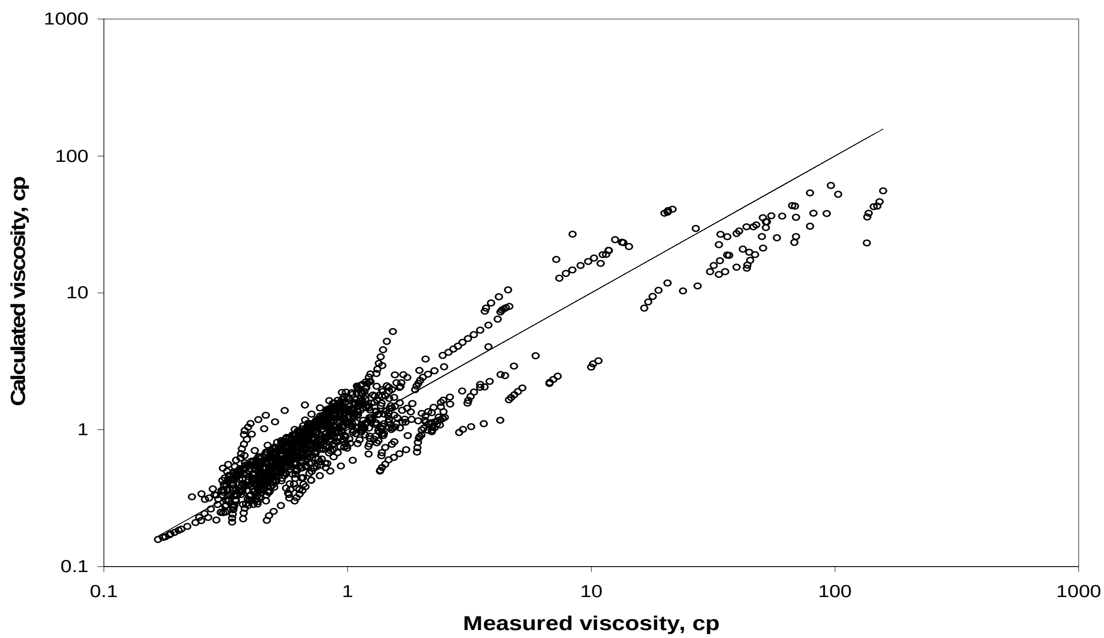

Fig. A.24- Graphical interpretation of the Bergman correlation for saturated oil viscosity on logarithmic coordinates.

The Hanafy *et al* correlation for saturated oil viscosity

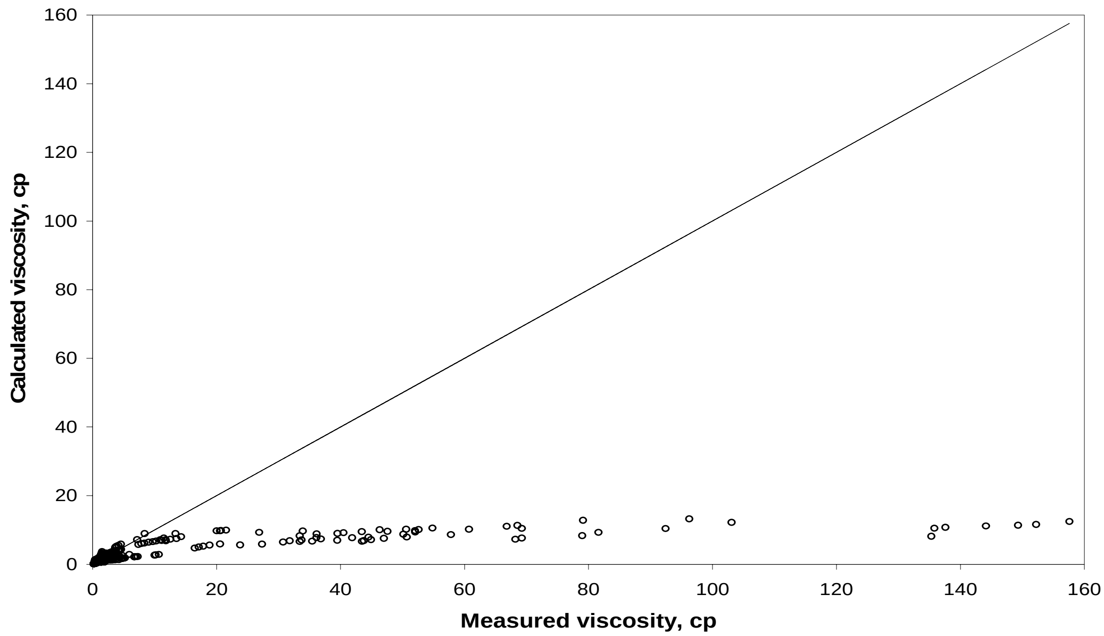

Fig. A.25- Graphical interpretation of the Hanafy *et al* correlation for saturated oil viscosity on Cartesian coordinates.

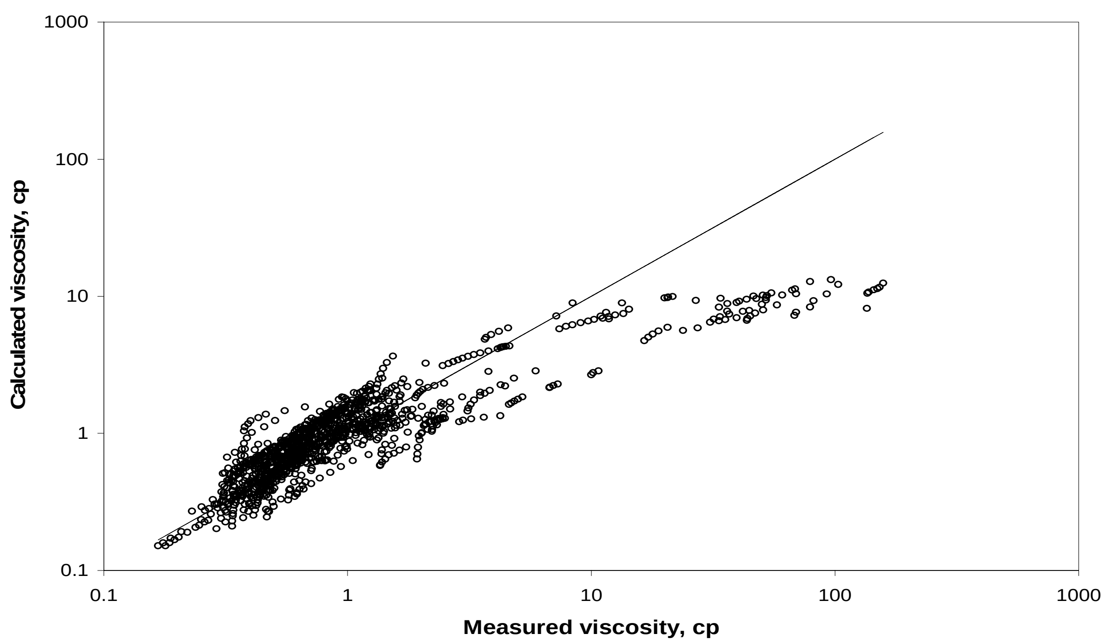

Fig. A.26- Graphical interpretation of the Hanafy *et al* correlation for saturated oil viscosity on logarithmic coordinates.

The Abu-Khamsin and Al-Marhoun correlation for saturated oil viscosity

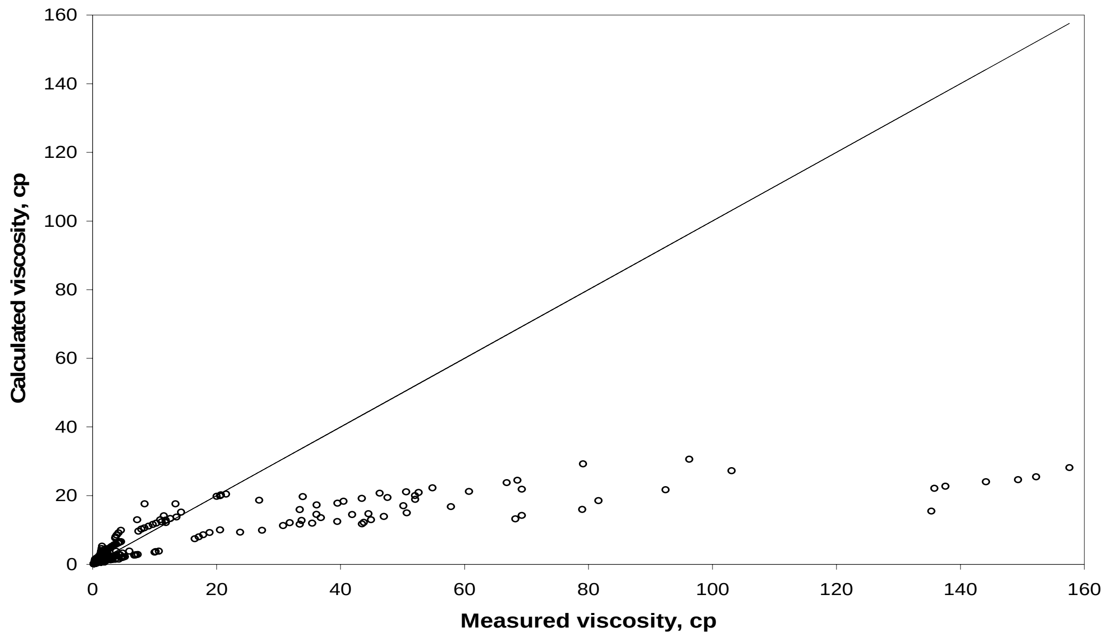

Fig. A.27- Graphical interpretation of the Abu-Khamsin and Al-Marhoun correlation for saturated oil viscosity on Cartesian coordinates.

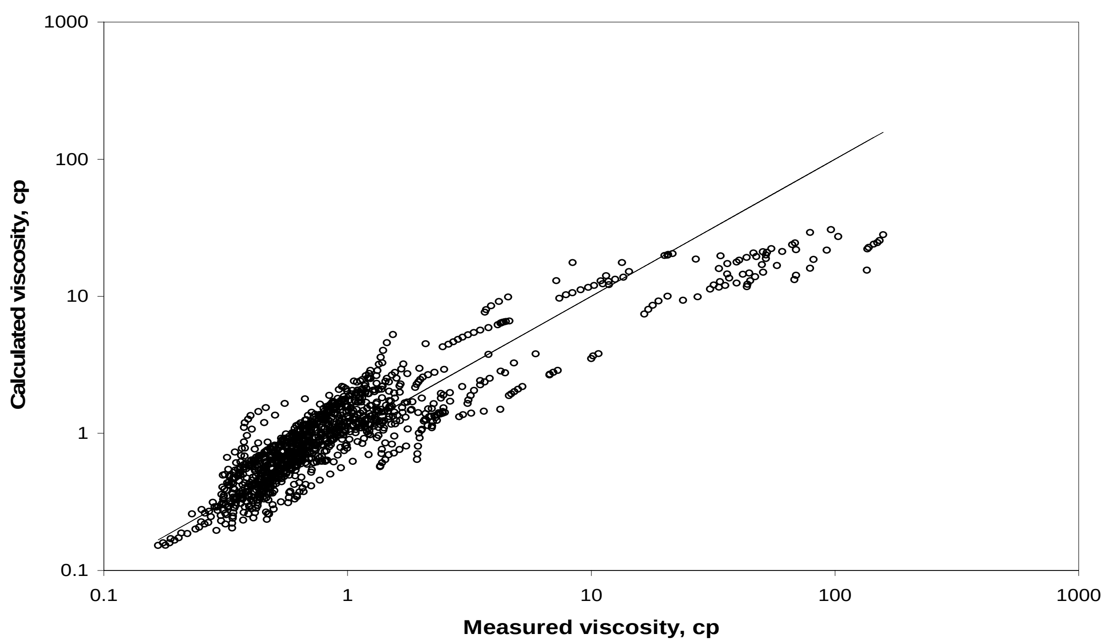

Fig. A.28- Graphical interpretation of the Abu-Khamsin and Al-Marhoun correlation for saturated oil viscosity on logarithmic coordinates.

The Elsharkawy and Alikhan correlation for saturated oil viscosity

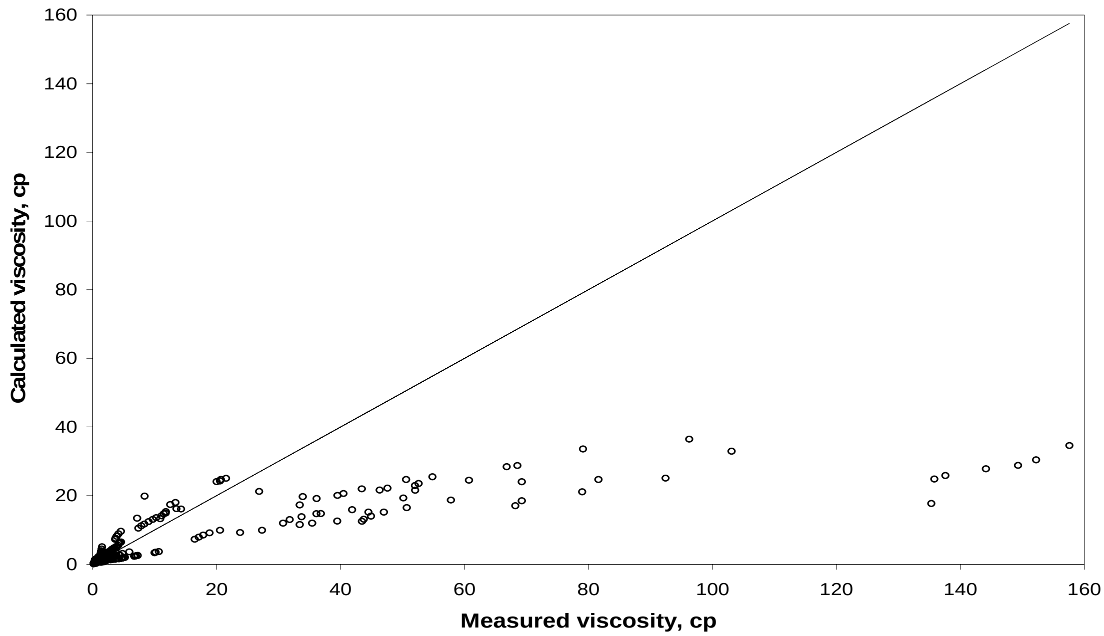

Fig. A.29- Graphical interpretation of the Elsharkawy and Alikhan correlation for saturated oil viscosity on Cartesian coordinates.

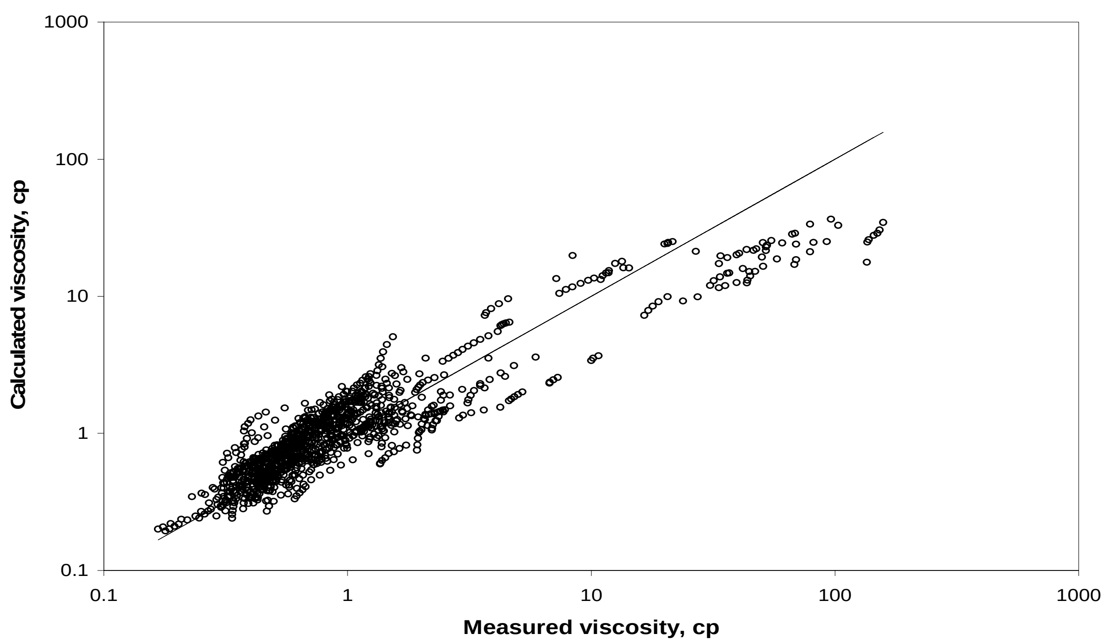

Fig. A.30- Graphical interpretation of the Elsharkawy and Alikhan correlation for saturated oil viscosity on logarithmic coordinates.

The Aziz, Govier, and Fogarasi correlation for saturated oil viscosity

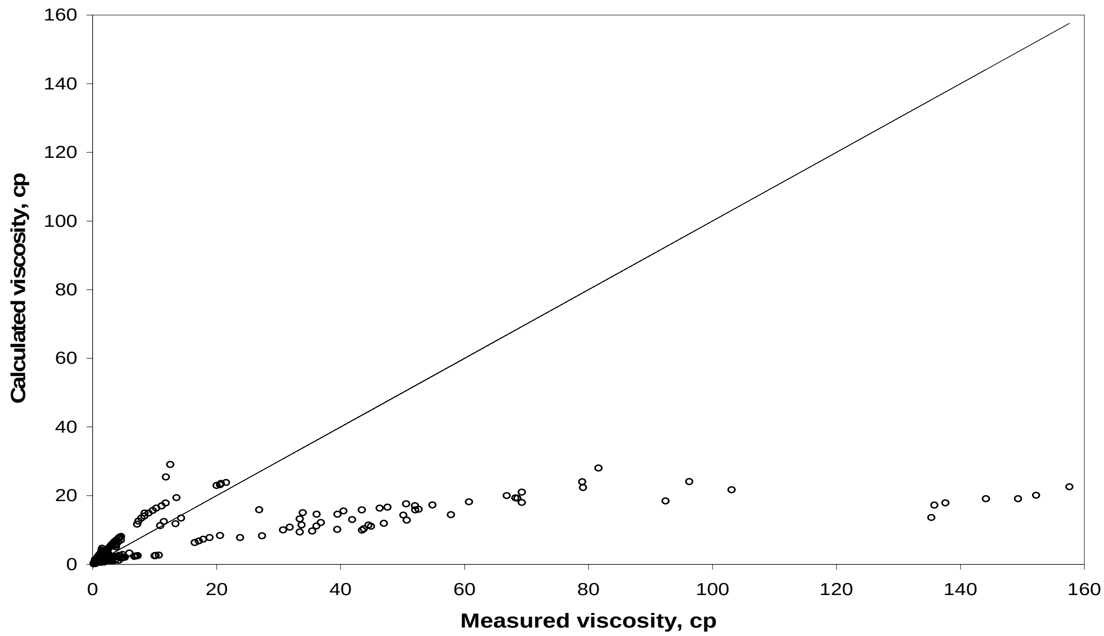

Fig. A.31- Graphical interpretation of the Aziz, Govier, and Fogarasi correlation for saturated oil viscosity on Cartesian coordinates.

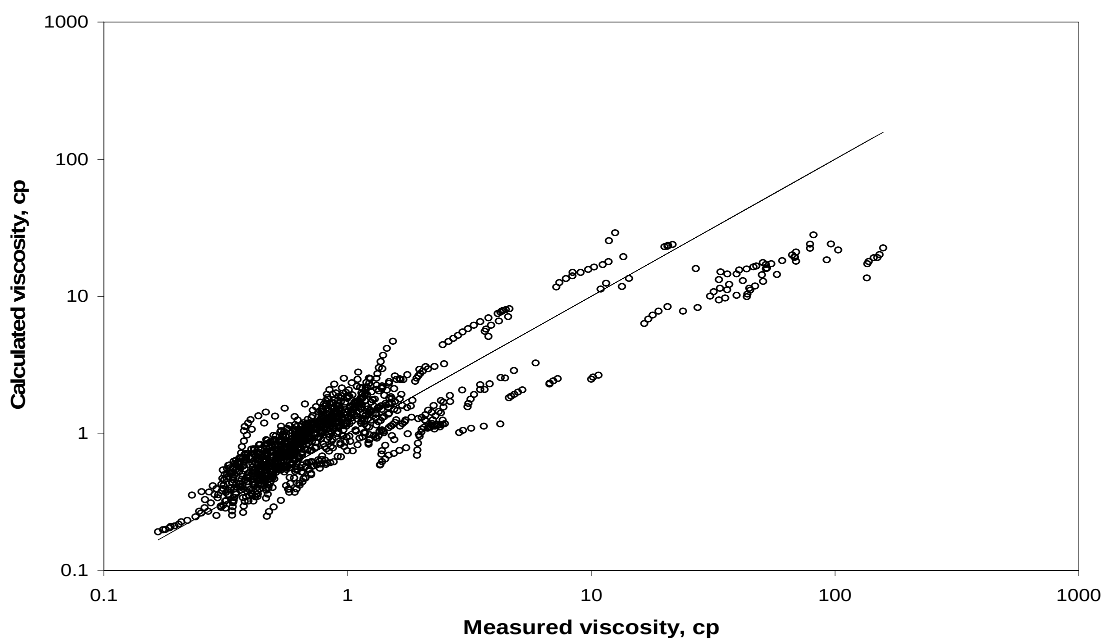

Fig. A.32- Graphical interpretation of the Aziz, Govier, and Fogarasi correlation for saturated oil viscosity on logarithmic coordinates.

The Khan *et al* correlation for saturated oil viscosity

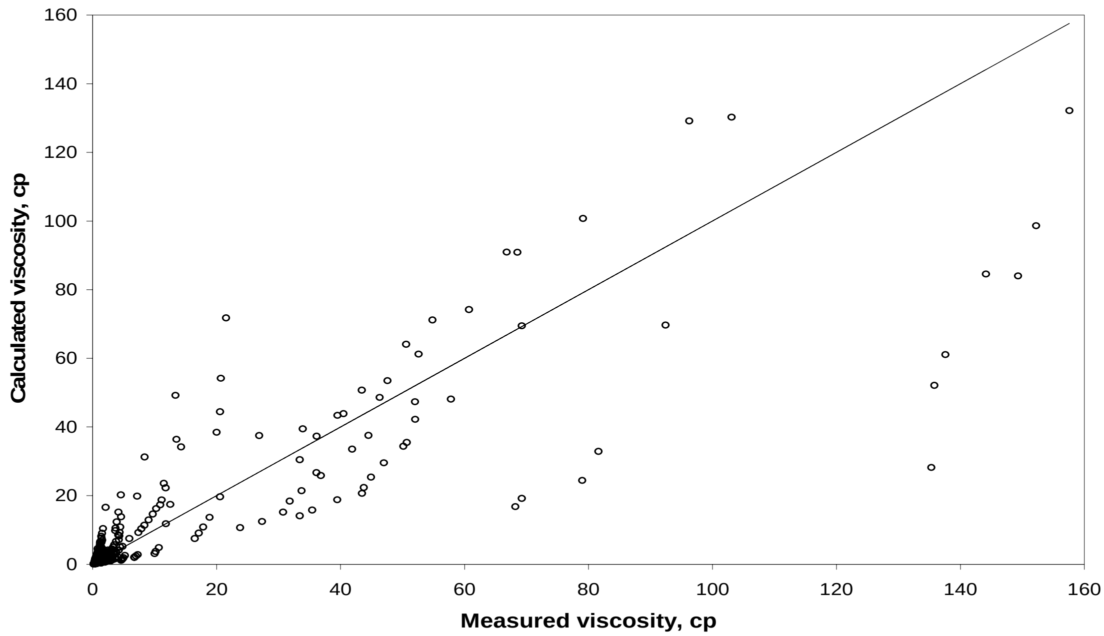

Fig. A.33- Graphical interpretation of the Khan *et al* correlation for saturated oil viscosity on Cartesian coordinates.

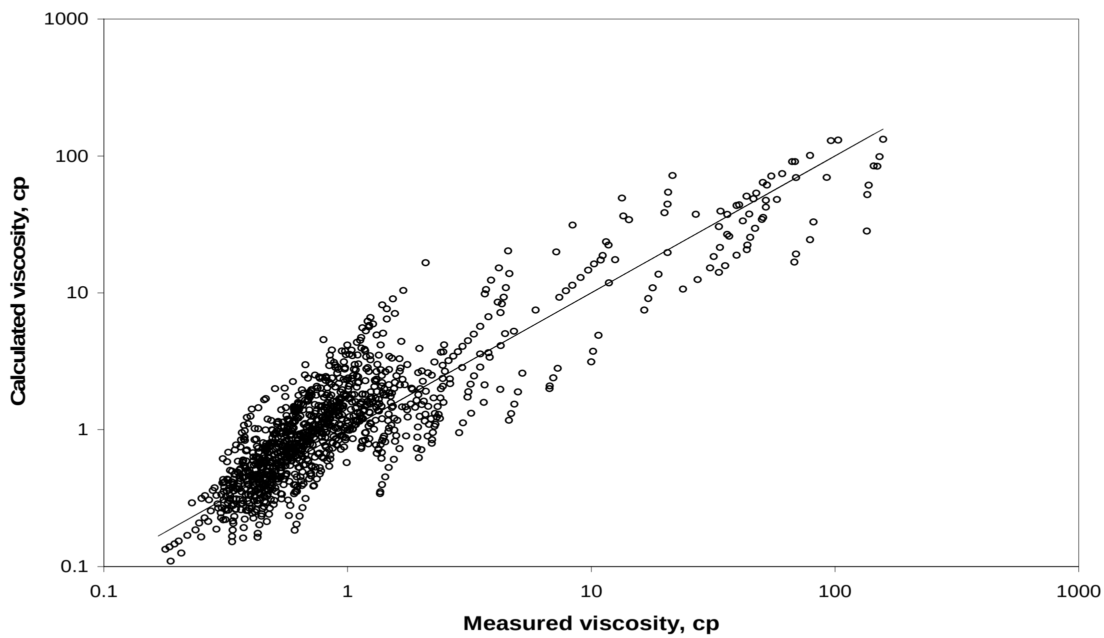

Fig. A.34- Graphical interpretation of the Khan *et al* correlation for saturated oil viscosity on logarithmic coordinates.

The Labedi correlation for saturated oil viscosity

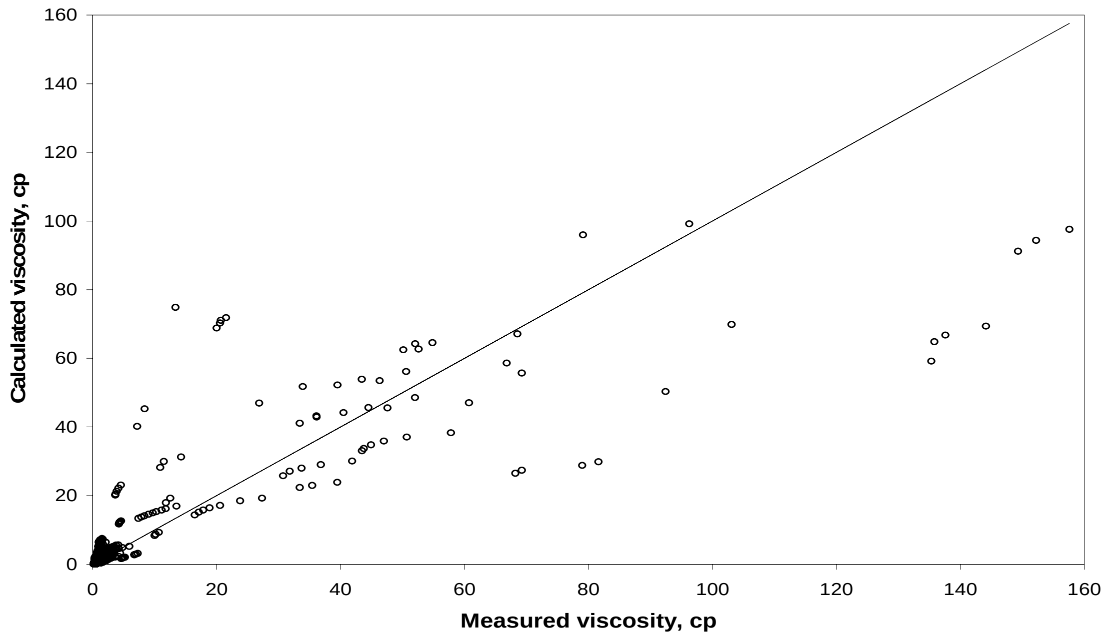

Fig. A.35- Graphical interpretation of the Labedi correlation for saturated oil viscosity on Cartesian coordinates.

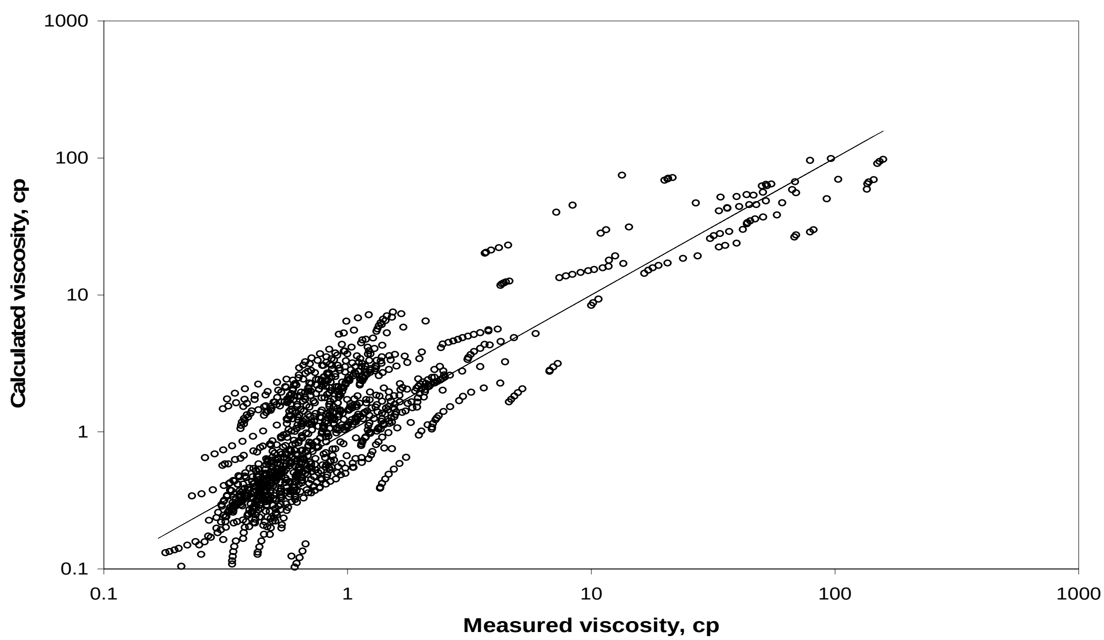

Fig. A.36- Graphical interpretation of the Labedi correlation for saturated oil viscosity on logarithmic coordinates.

APPENDIX B

PERFORMANCE OF VISCOSITY CORRELATIONS FOR UMDERSATURATED RESERVOIR OIL (183 PVT REPORTS/ 1968 DATA POINTS)

The proposed correlation for undersaturated oil viscosity

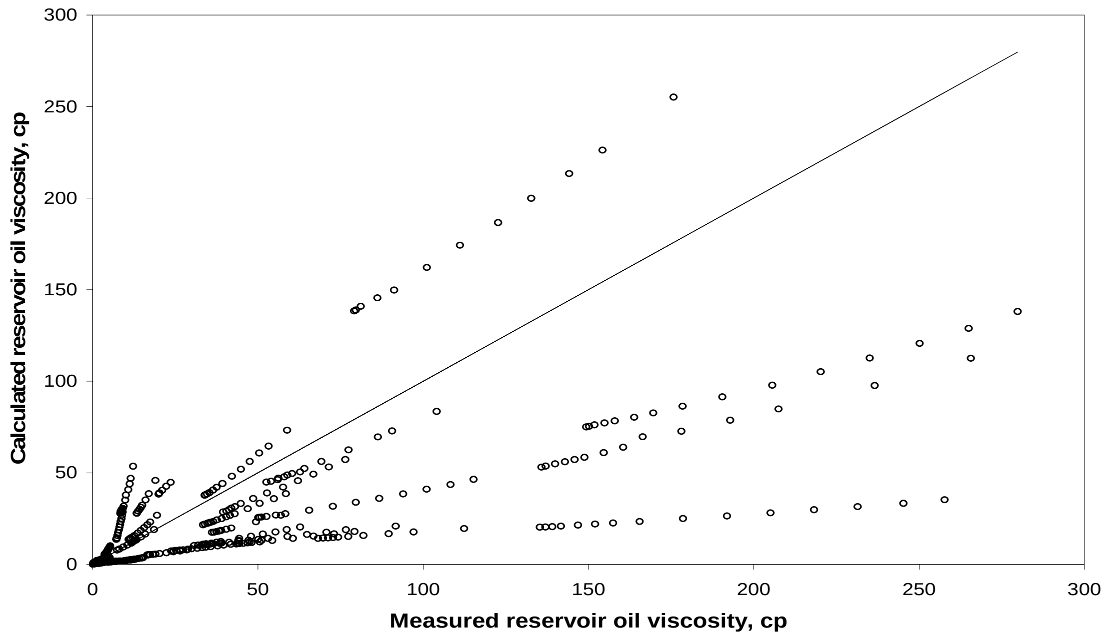

Fig. B.1- Graphical interpretation of the proposed correlation for undersaturated oil viscosity on Cartesian coordinates.

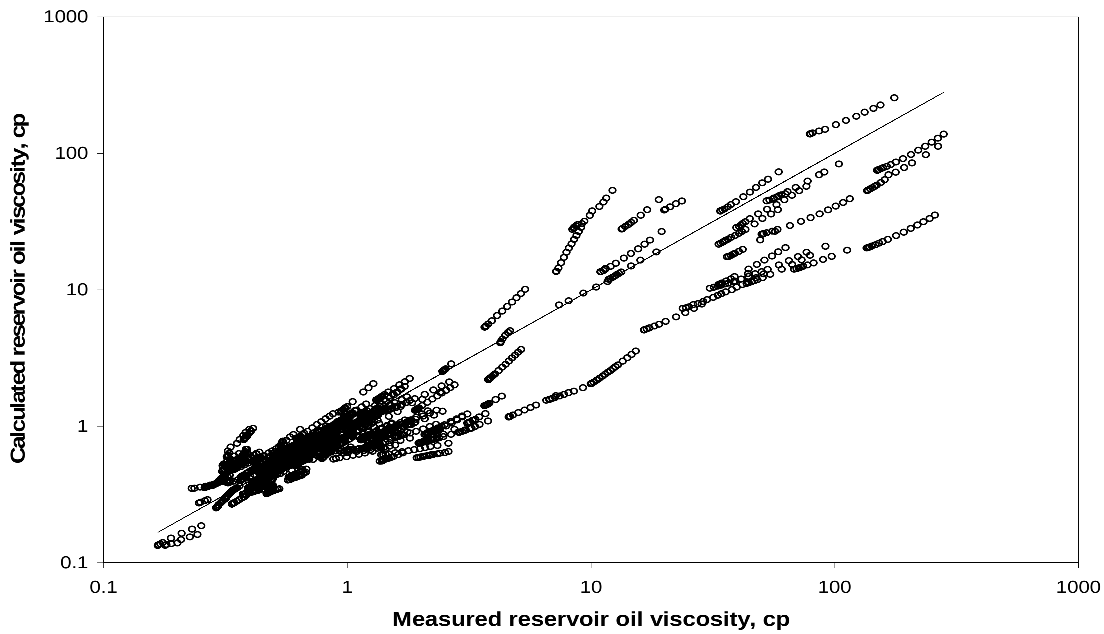

Fig. B.2- Graphical interpretation of the proposed correlation for undersaturated oil viscosity on logarithmic coordinates.

The Dindoruk and Christman correlation for undersaturated oil viscosity

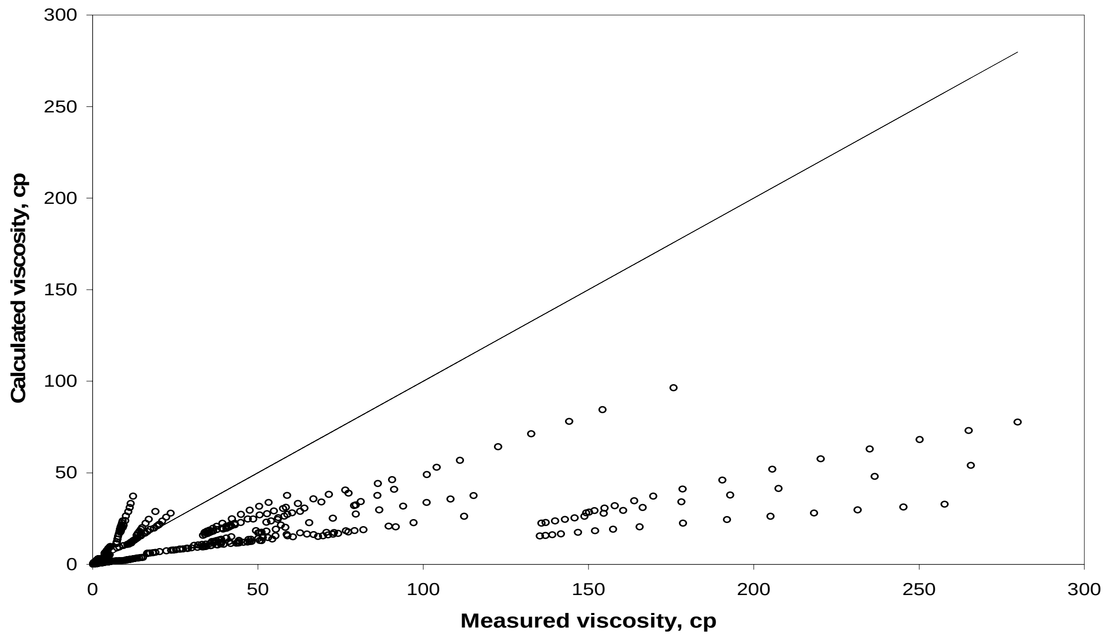

Fig. B.3- Graphical interpretation of the Dindoruk and Christman correlation for undersaturated oil viscosity on Cartesian coordinates.

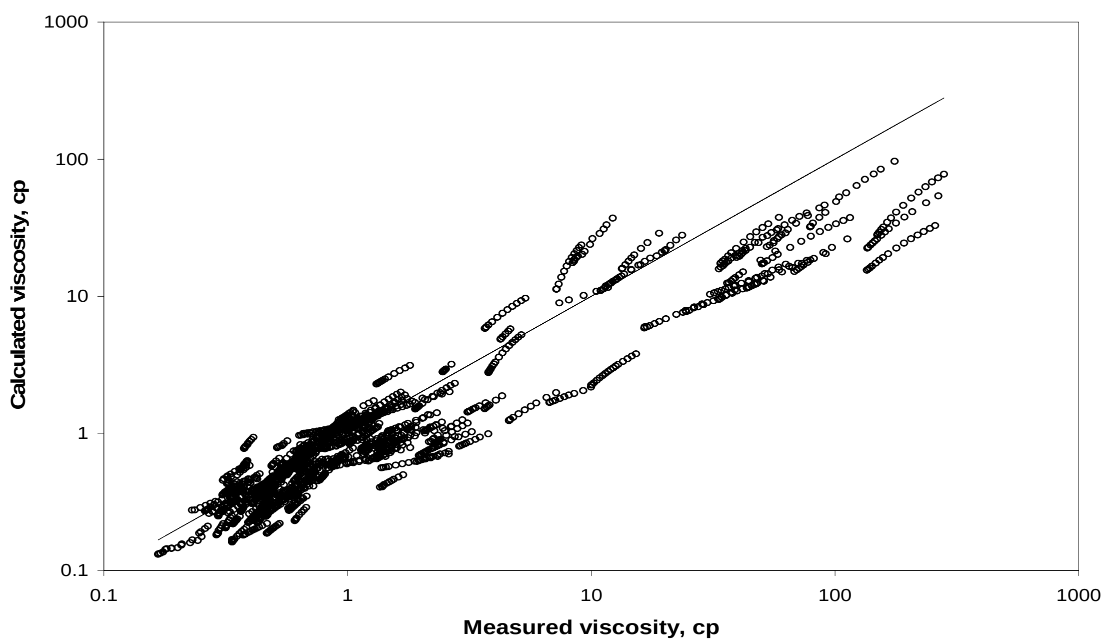

Fig. B.4- Graphical interpretation of the Dindoruk and Christman correlation for undersaturated oil viscosity on logarithmic coordinates.

The Petrosky and Farshad correlation for undersaturated oil viscosity

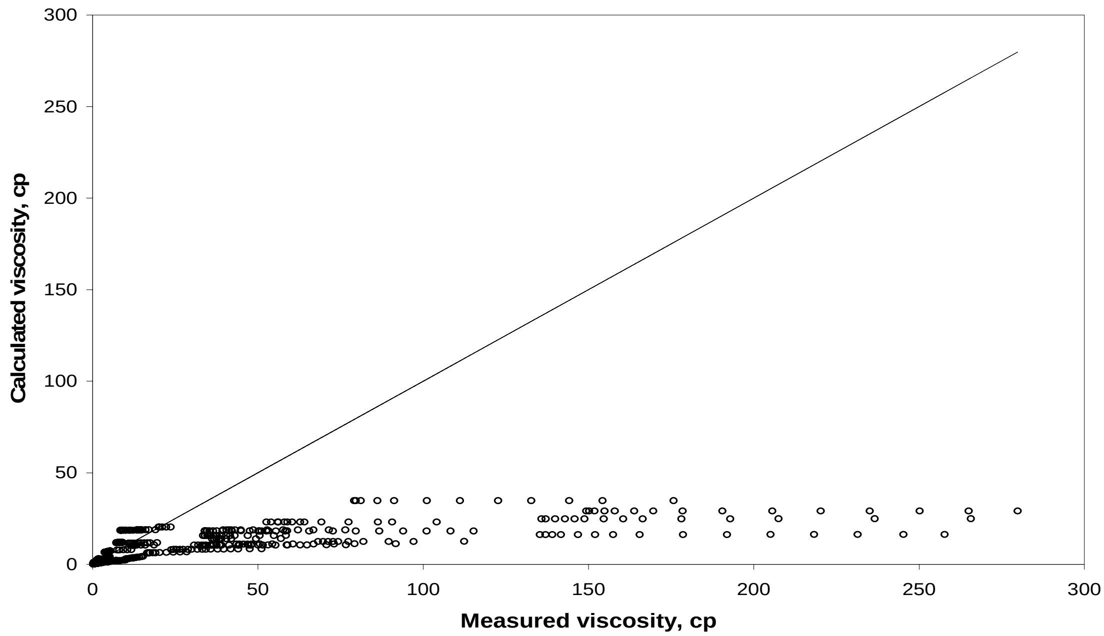

Fig. B.5- Graphical interpretation of the Petrosky and Farshad correlation for undersaturated oil viscosity on Cartesian coordinates.

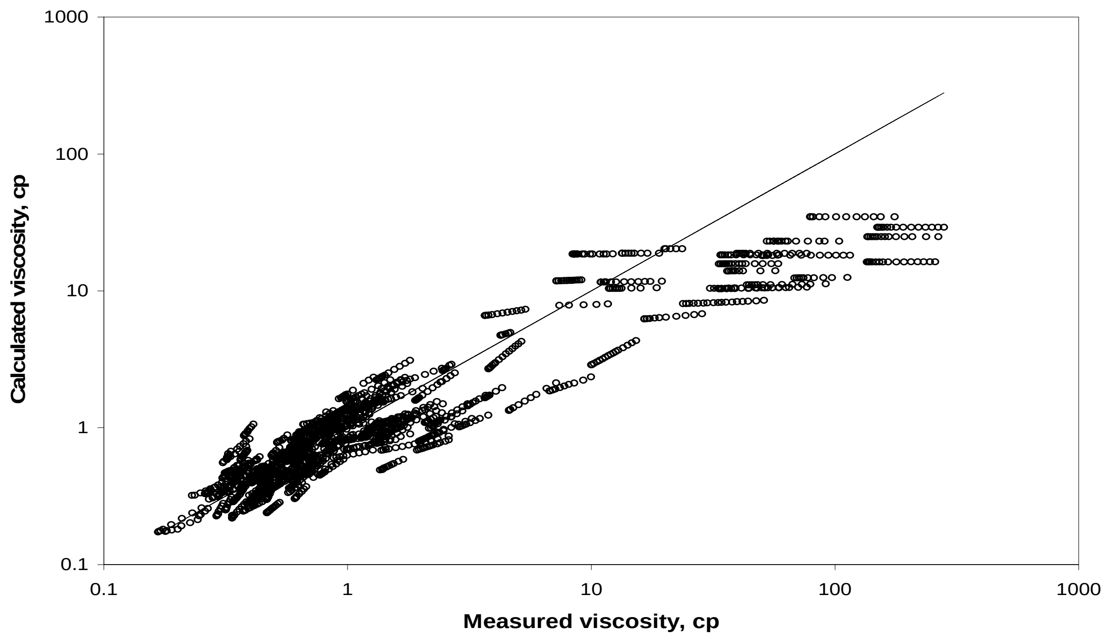

Fig. B.6- Graphical interpretation of the Petrosky and Farshad correlation for undersaturated oil viscosity on logarithmic coordinates.

The Vasquez and Beggs correlation for undersaturated oil viscosity

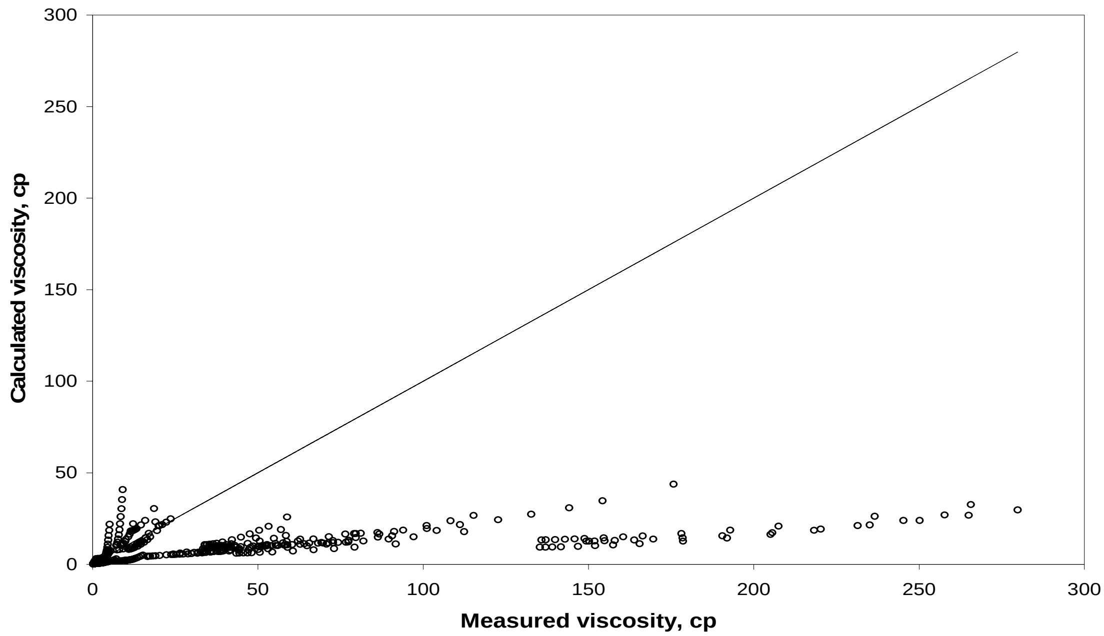

Fig. B.7- Graphical interpretation of the Vasquez and Beggs correlation for undersaturated oil viscosity on Cartesian coordinates.

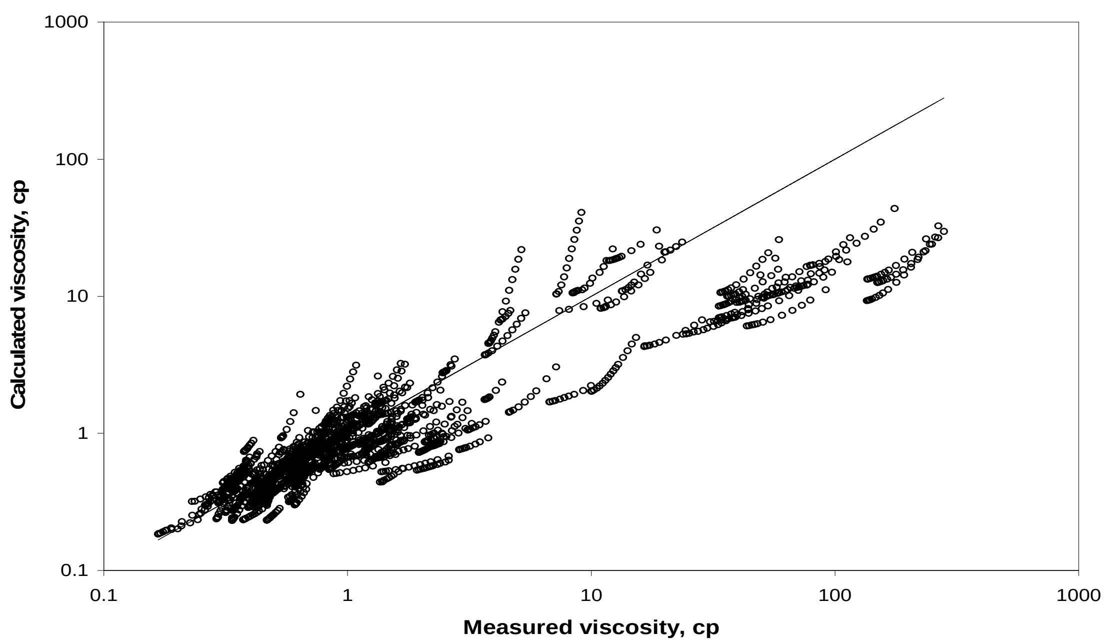

Fig. B.8- Graphical interpretation of the Vasquez and Beggs correlation for undersaturated oil viscosity on logarithmic coordinates.

The McCain correlation for undersaturated oil viscosity

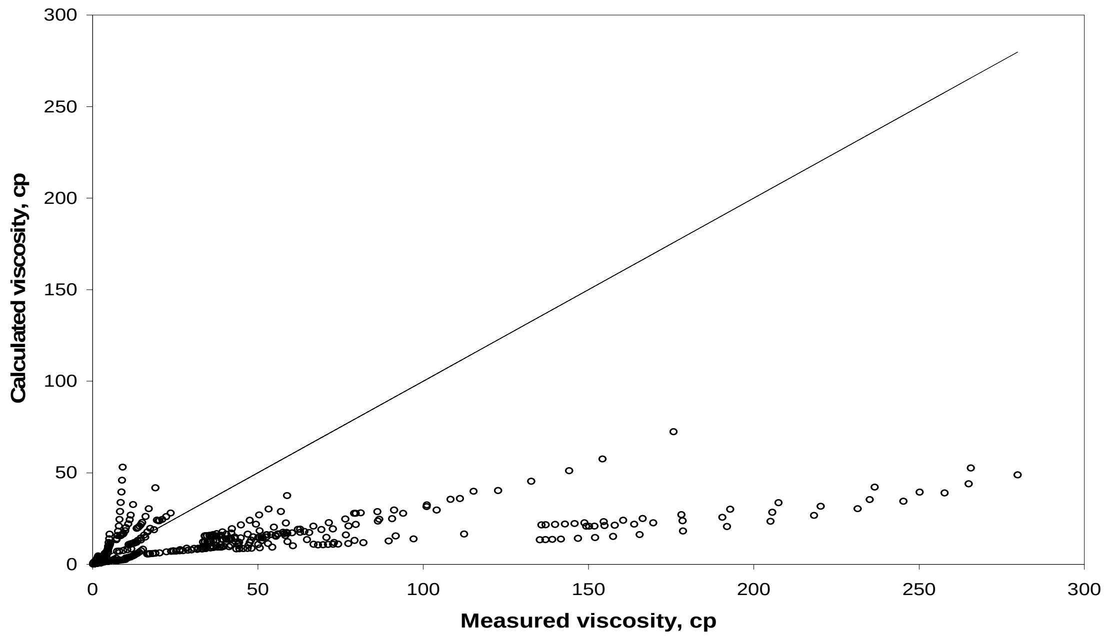

Fig. B.9- Graphical interpretation of the McCain correlation for undersaturated oil viscosity on Cartesian coordinates.

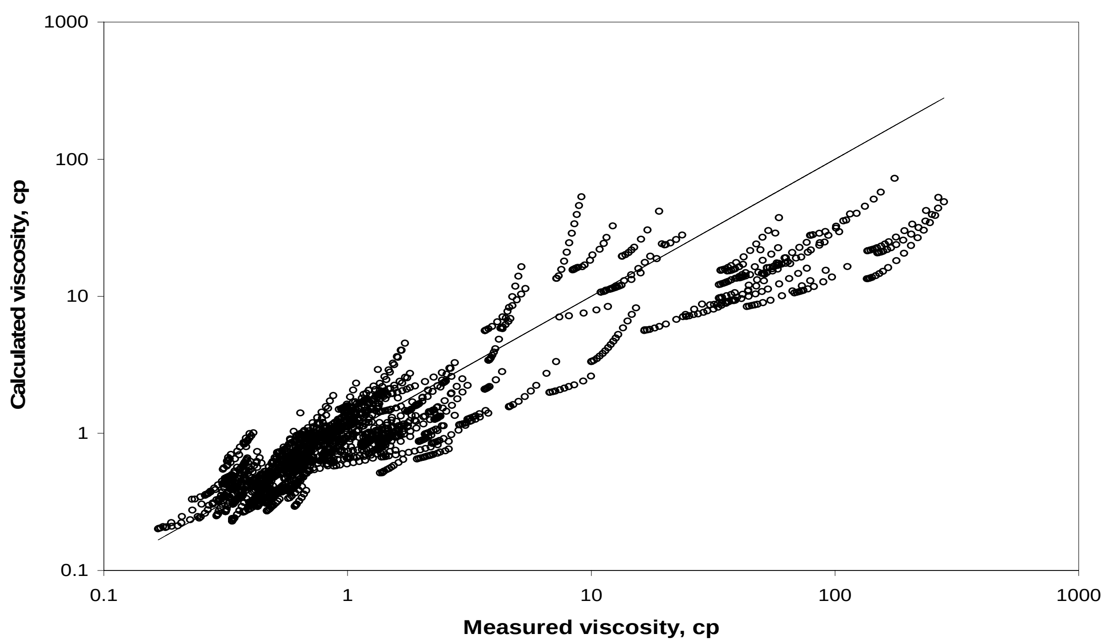

Fig. B.10- Graphical interpretation of the McCain correlation for undersaturated oil viscosity on logarithmic coordinates.

The De Ghetto, Paone, and Villa correlation for undersaturated oil viscosity

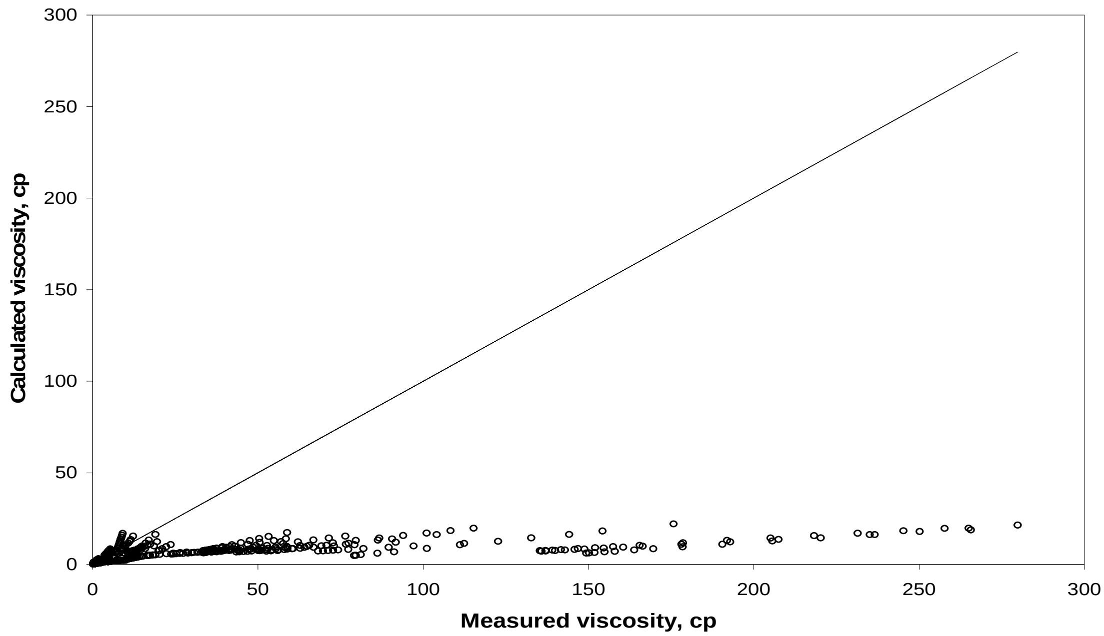

Fig. B.11- Graphical interpretation of the De Ghetto, Paone, and Villa correlation for undersaturated oil viscosity on Cartesian coordinates.

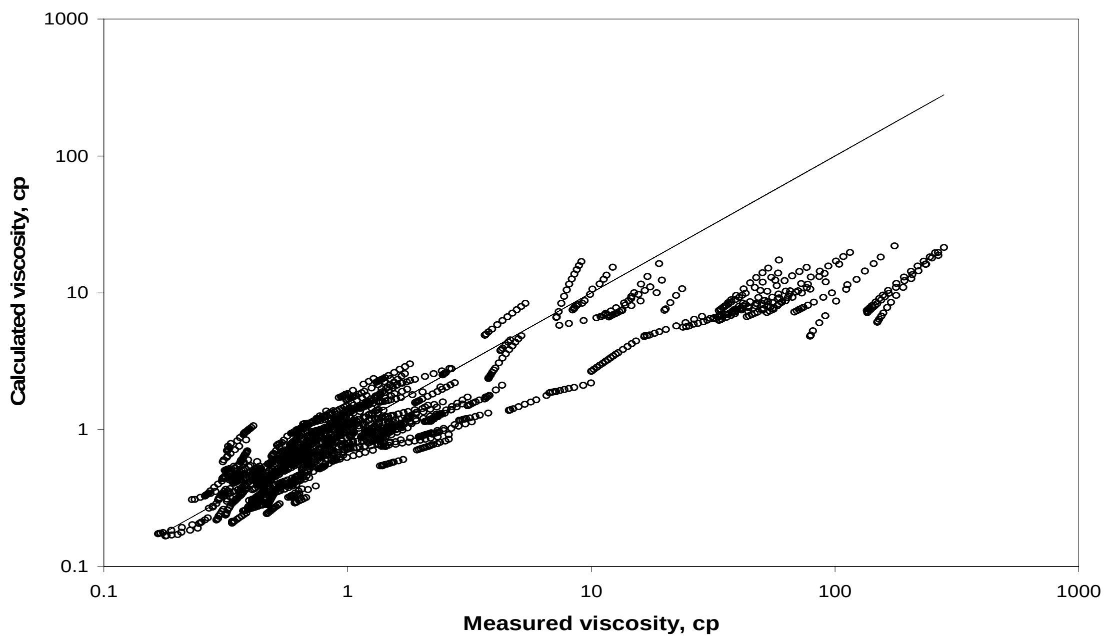

Fig. B.12- Graphical interpretation of the De Ghetto, Paone, and Villa correlation for undersaturated oil viscosity on logarithmic coordinates.

The Standing correlation for undersaturated oil viscosity

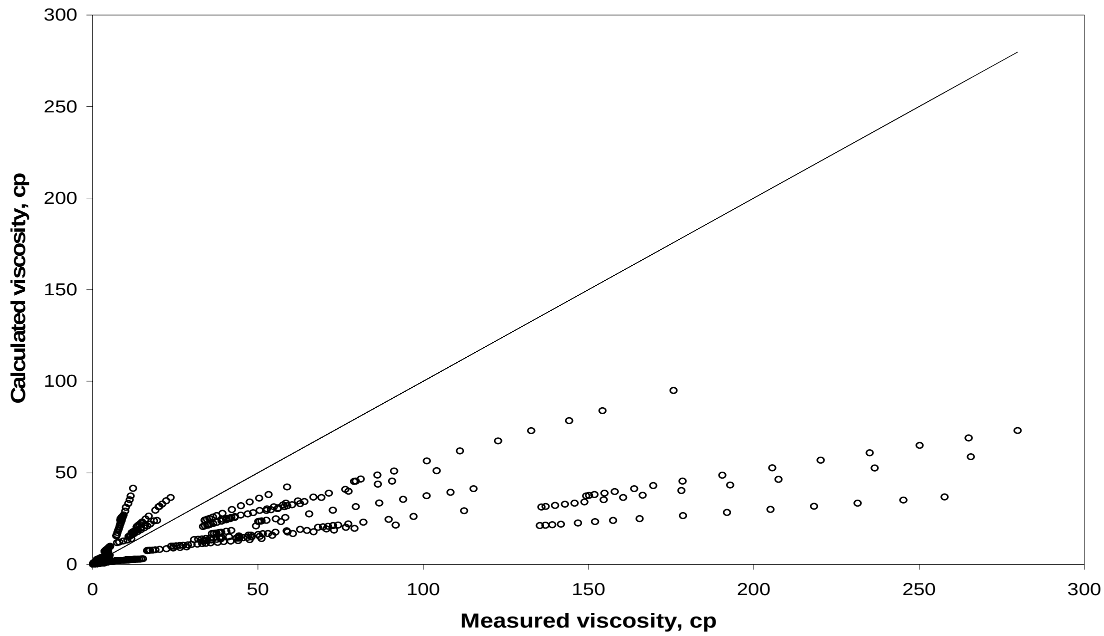

Fig. B.13- Graphical interpretation of the Standing correlation for undersaturated oil viscosity on Cartesian coordinates.

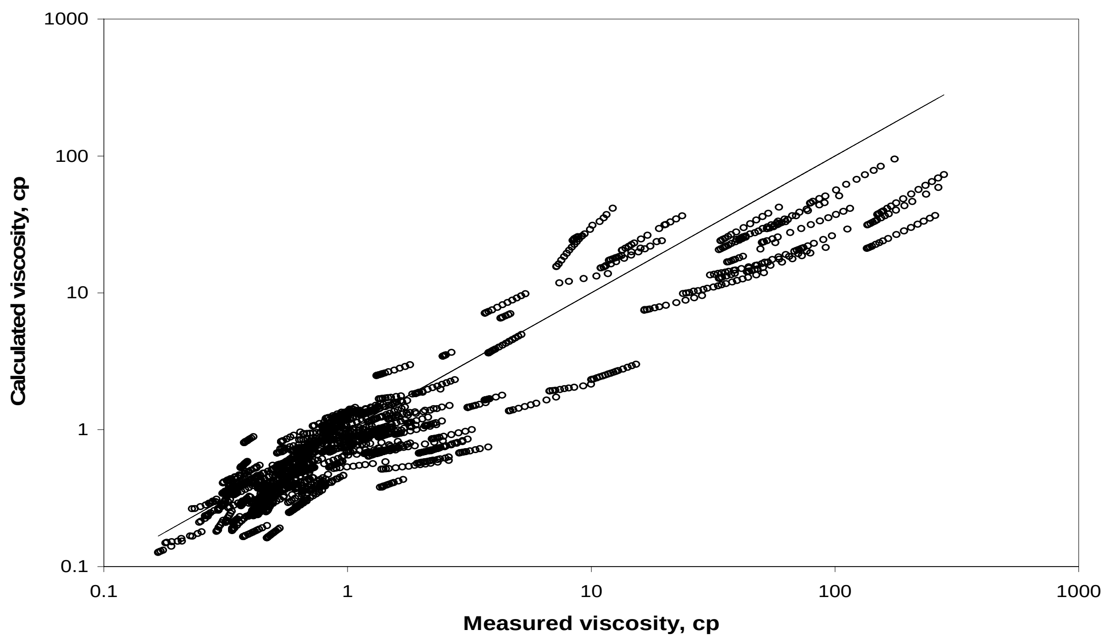

Fig. B.14- Graphical interpretation of the Standing correlation for undersaturated oil viscosity on logarithmic coordinates.

The Hanafy *et al.* correlation for undersaturated oil viscosity

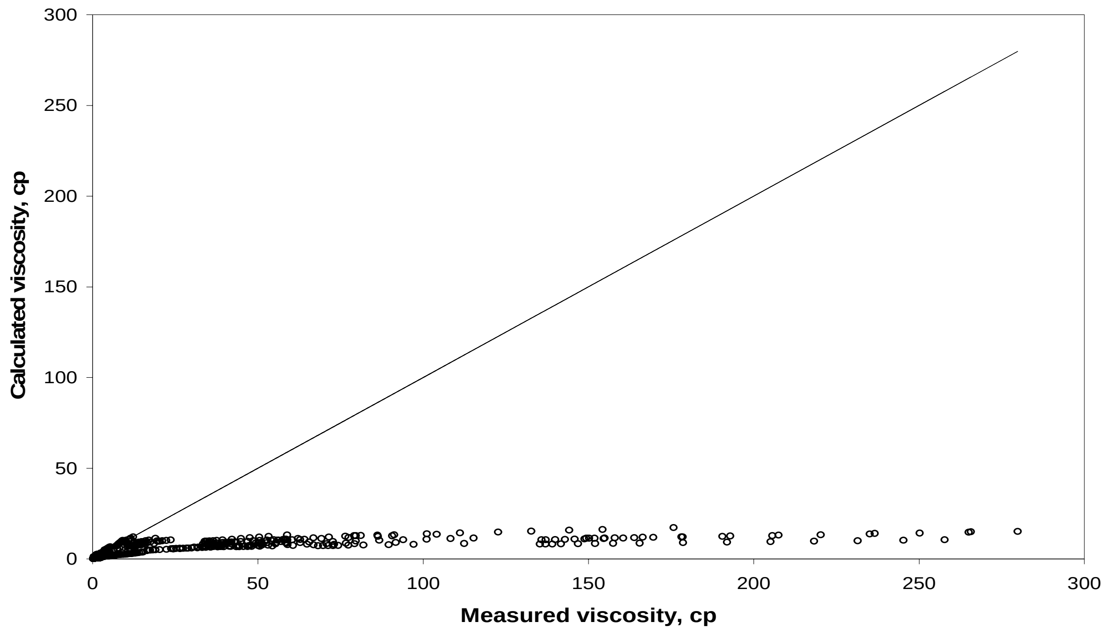

Fig. B.15- Graphical interpretation of the Hanafy *et al.* correlation for undersaturated oil viscosity on Cartesian coordinates.

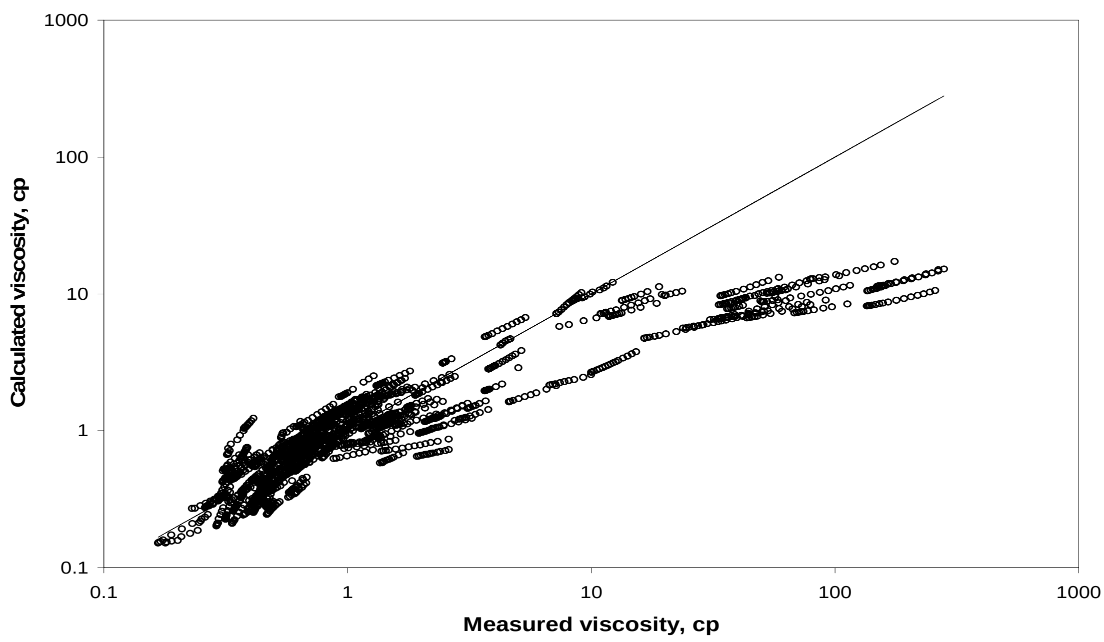

Fig. B.16- Graphical interpretation of the Hanafy *et al.* correlation for undersaturated oil viscosity on logarithmic coordinates.

The Elsharkawy and Alikhan correlation for undersaturated oil viscosity

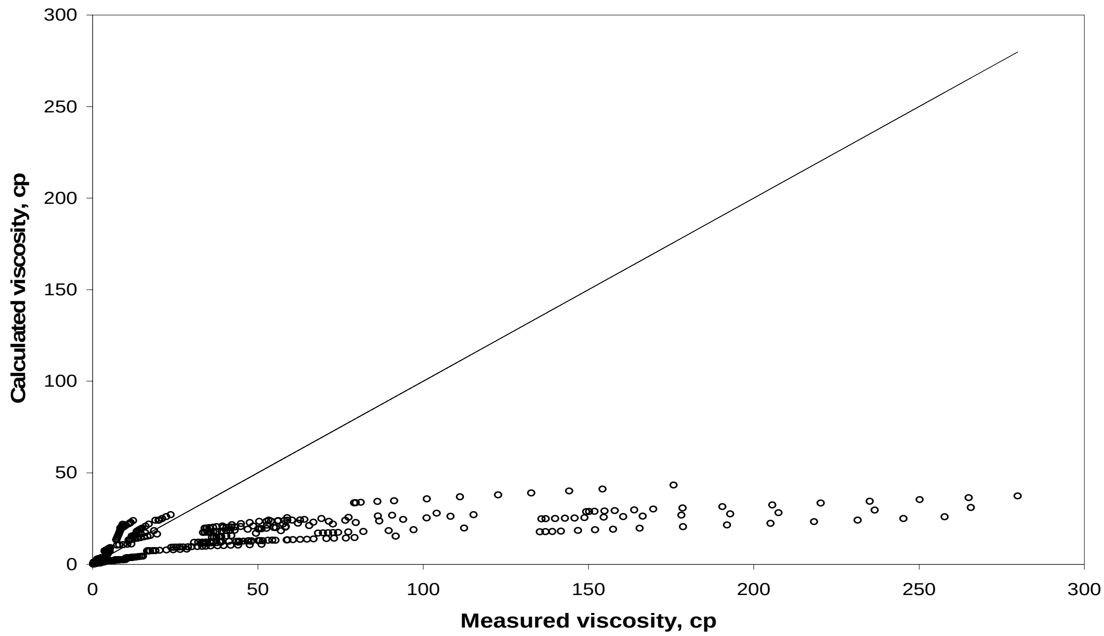

Fig. B.17- Graphical interpretation of the Elsharkawy and Alikhan correlation for undersaturated oil viscosity on Cartesian coordinates.

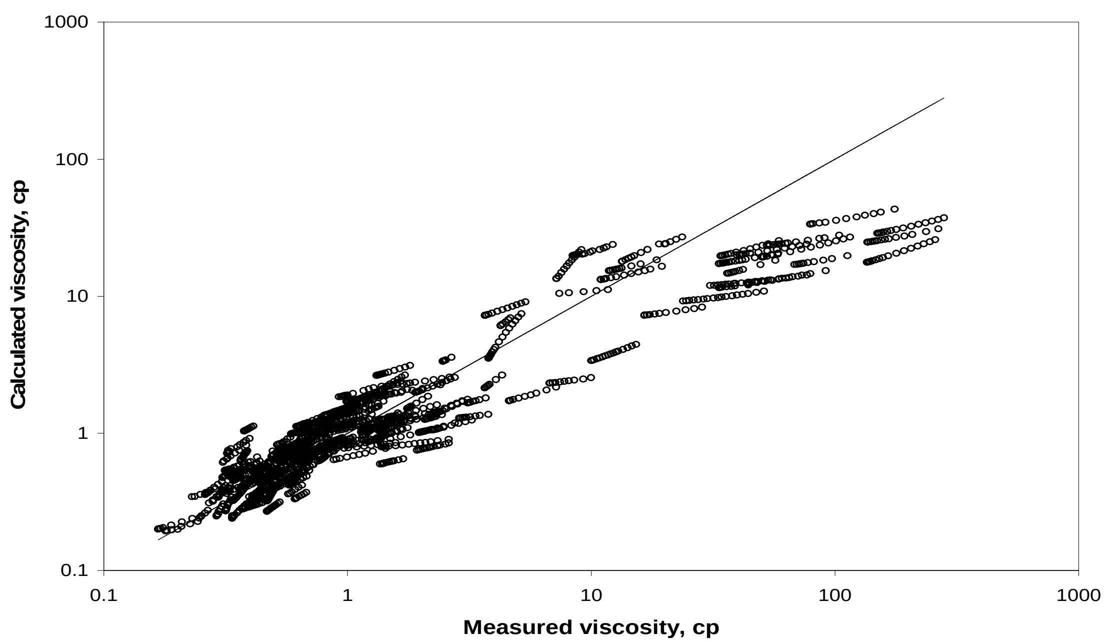

Fig. B.18- Graphical interpretation of the Elsharkawy and Alikhan correlation for undersaturated oil viscosity on logarithmic coordinates.

The Abu-Khamsin and Al-Marhoun correlation for undersaturated oil viscosity

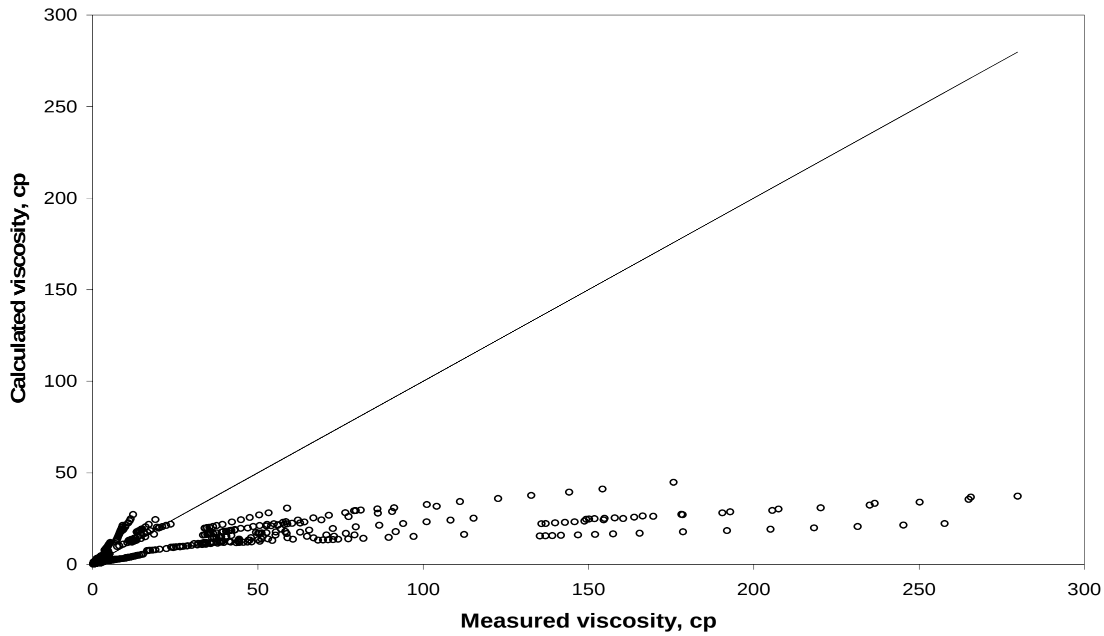

Fig. B.19- Graphical interpretation of the Abu-Khamsin and Al-Marhoun correlation for undersaturated oil viscosity on Cartesian coordinates.

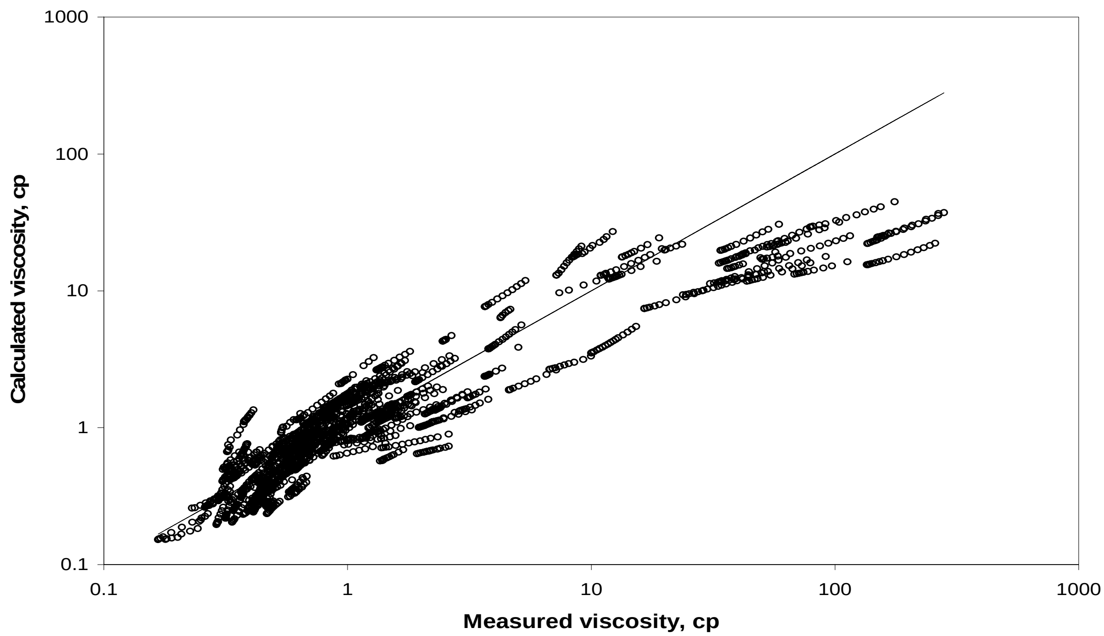

Fig. B.20- Graphical interpretation of the Abu-Khamsin and Al-Marhoun correlation for undersaturated oil viscosity on logarithmic coordinates.

The Almehaideb correlation for undersaturated oil viscosity

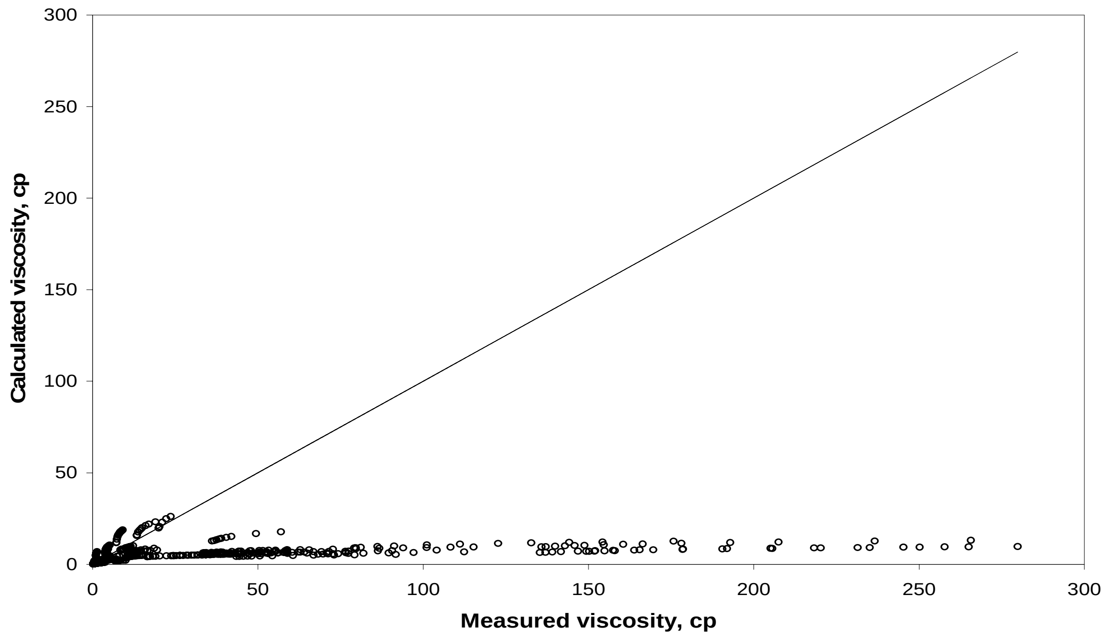

Fig. B.21- Graphical interpretation of the Almehaideb correlation for undersaturated oil viscosity on Cartesian coordinates.

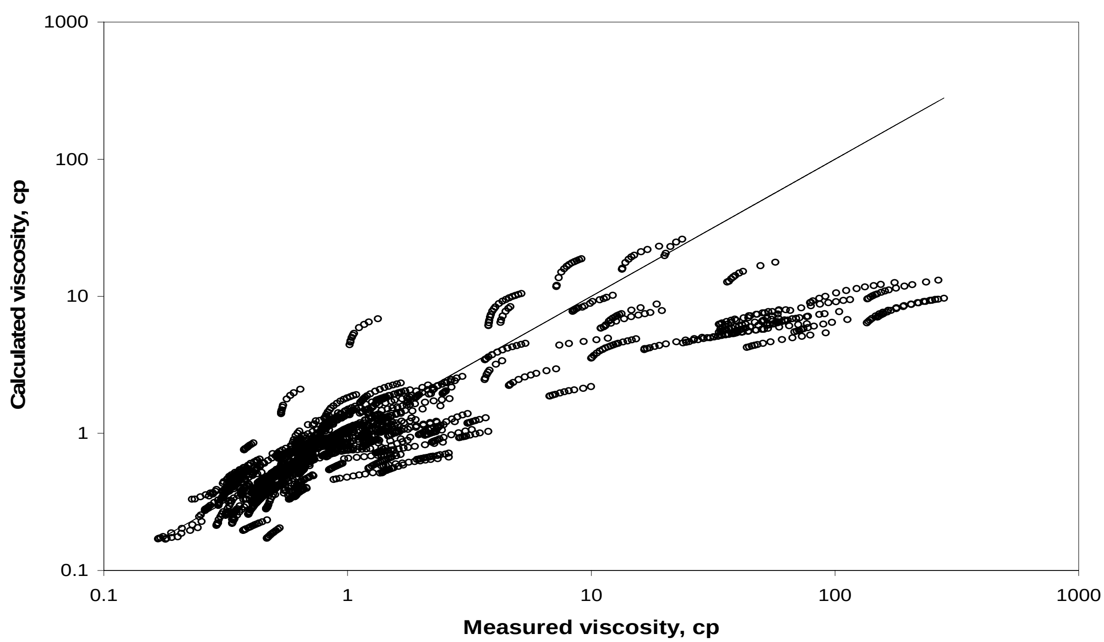

Fig. B.22- Graphical interpretation of the Almehaideb correlation for undersaturated oil viscosity on logarithmic coordinates.

The Kartoatmodjo and Schmidt correlation for undersaturated oil viscosity

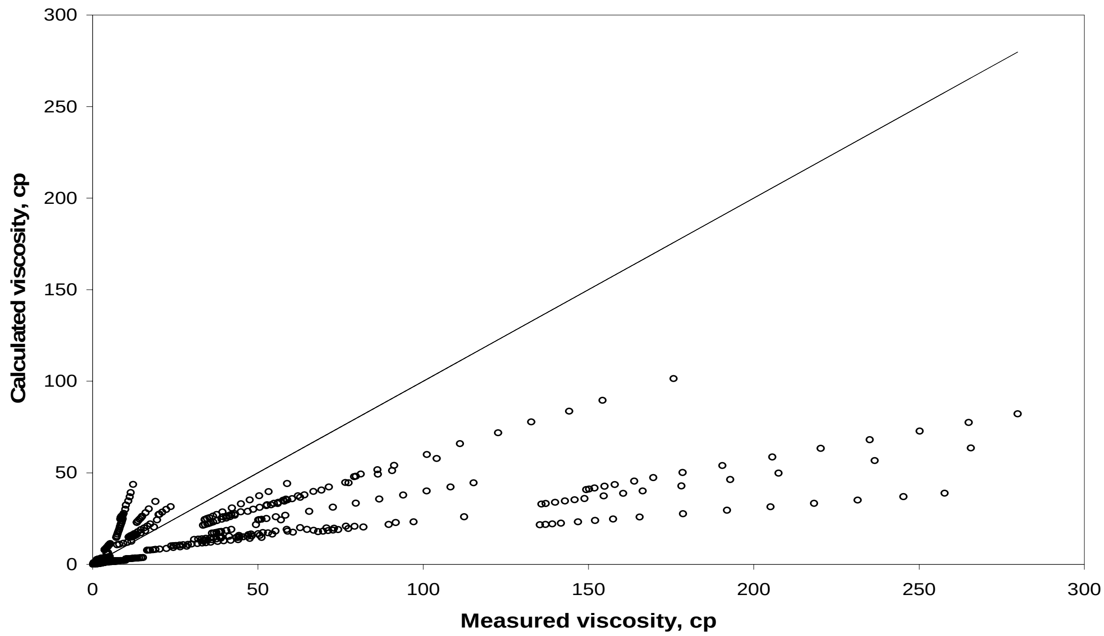

Fig. B.23- Graphical interpretation of the Kartoatmodjo and Schmidt correlation for undersaturated oil viscosity on Cartesian coordinates.

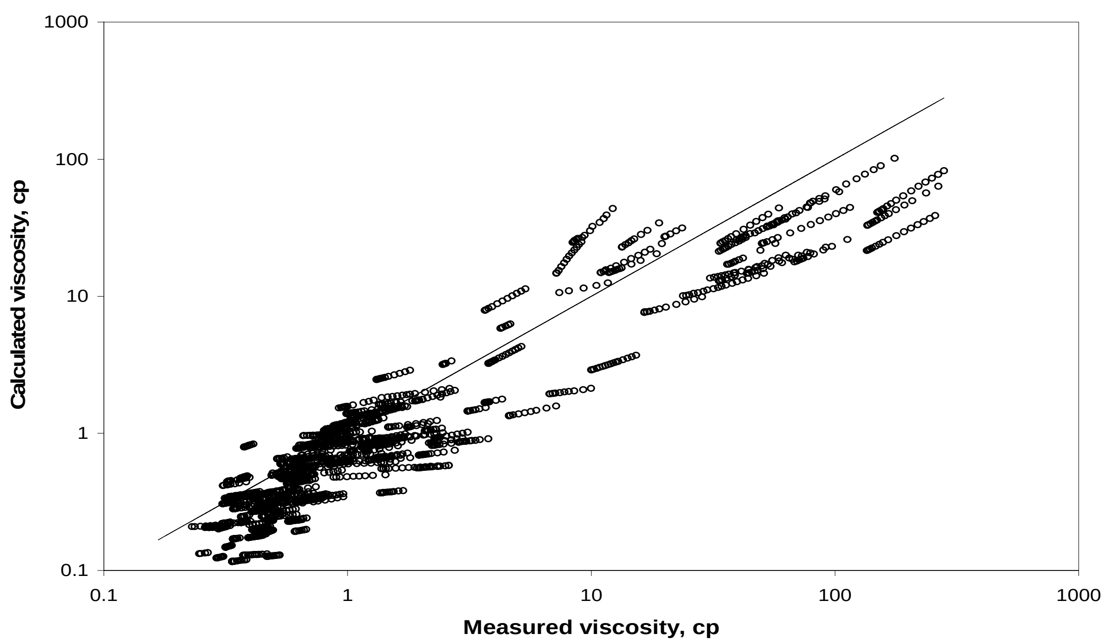

Fig. B.24- Graphical interpretation of the Kartoatmodjo and Schmidt correlation for undersaturated oil viscosity on logarithmic coordinates.

The Elsharkwy and Gharbi correlation for undersaturated oil viscosity

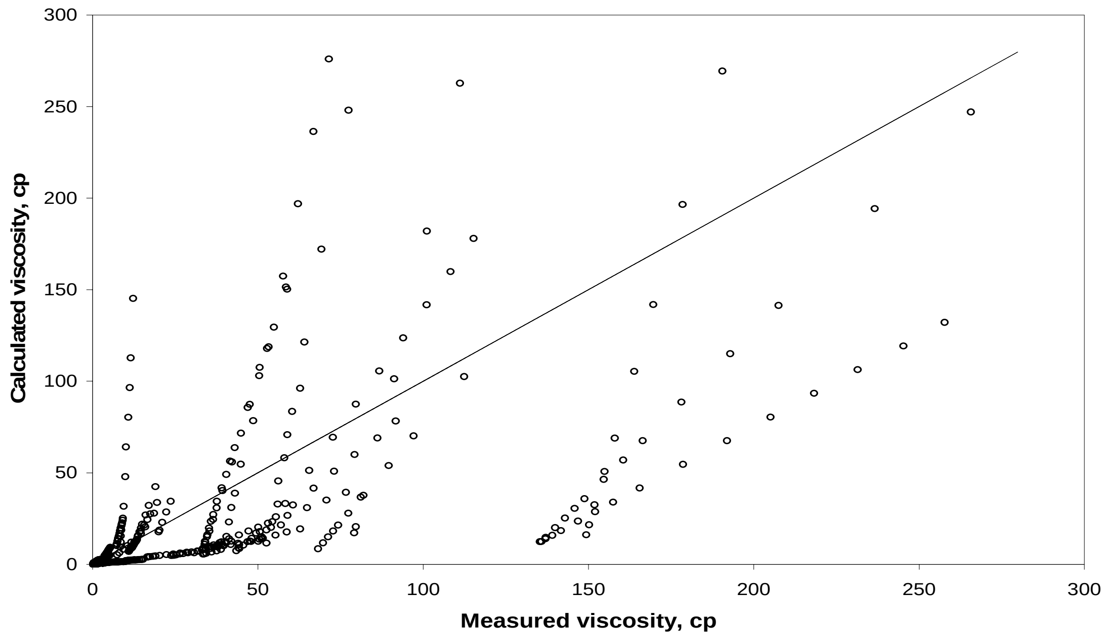

Fig. B.25- Graphical interpretation of the Elsharkwy and Gharbi correlation for undersaturated oil viscosity on Cartesian coordinates.

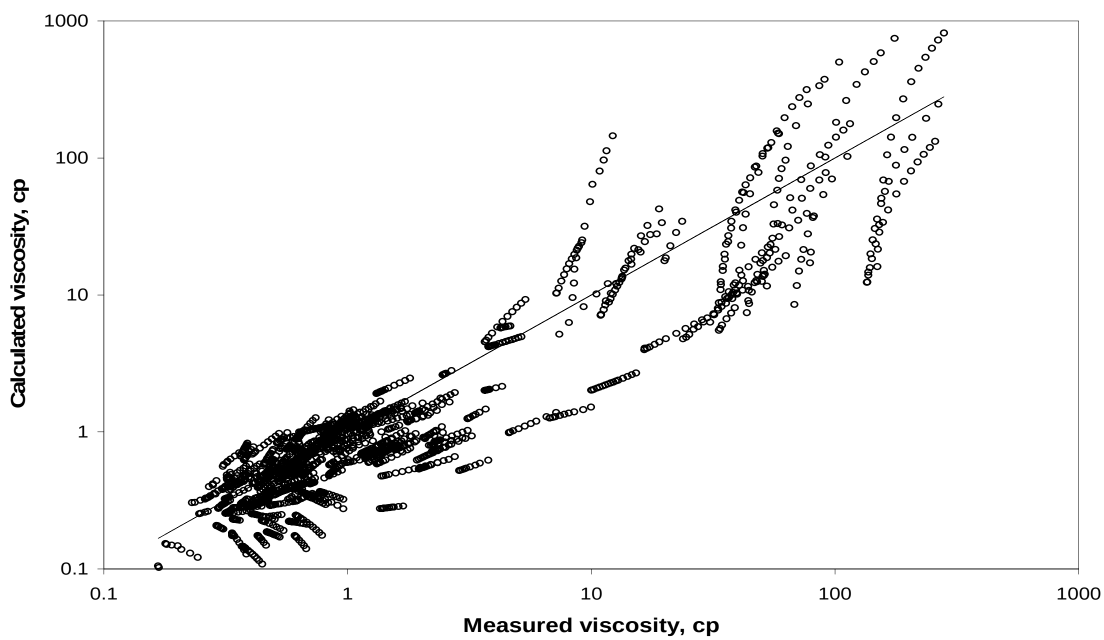

Fig. B.26- Graphical interpretation of the Elsharkwy and Gharbi correlation for undersaturated oil viscosity on logarithmic coordinates.

The Khan *et al.* correlation for undersaturated oil viscosity

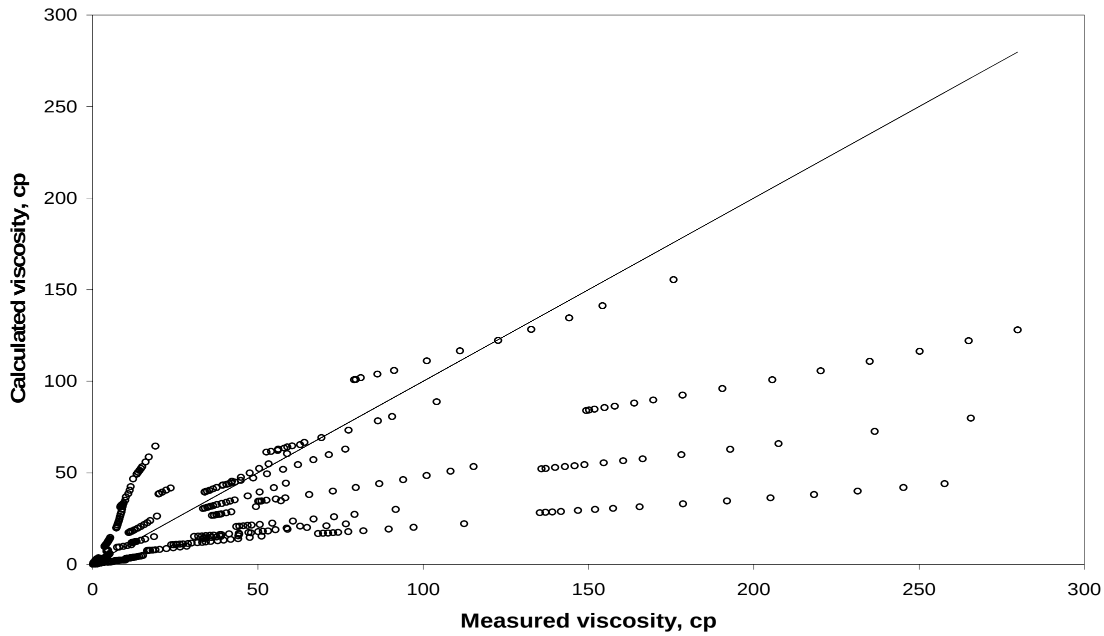

Fig. B.27- Graphical interpretation of the Khan *et al.* correlation for undersaturated oil viscosity on Cartesian coordinates.

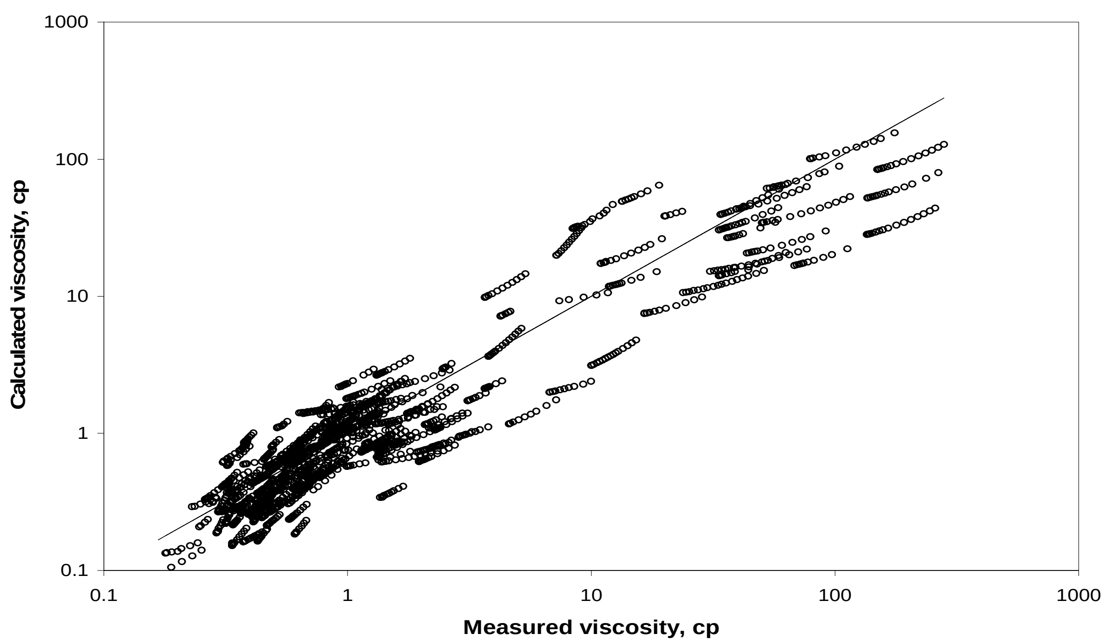

Fig. B.28- Graphical interpretation of the Khan *et al.* correlation for undersaturated oil viscosity on logarithmic coordinates.

The Al-Khafaji, Abdul-Majeed, and Hassoon correlation for undersaturated oil viscosity

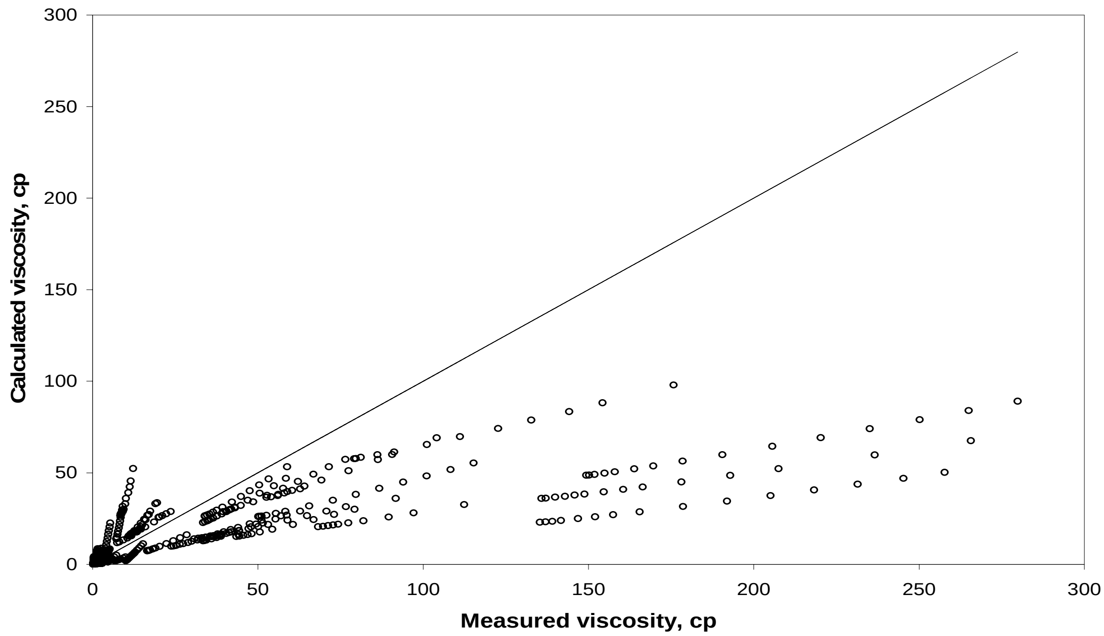

Fig. B.29- Graphical interpretation of the Al-Khafaji, Abdul-Majeed, and Hassoon correlation for undersaturated oil viscosity on Cartesian coordinates.

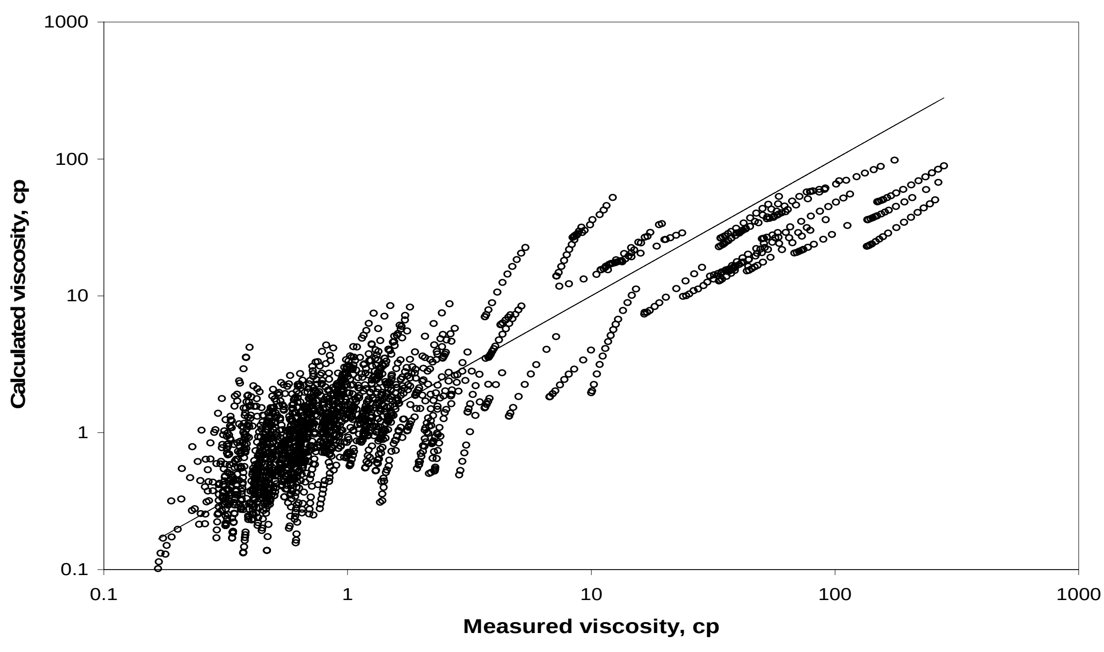

Fig. B.30- Graphical interpretation of the Al-Khafaji, Abdul-Majeed, and Hassoon correlation for undersaturated oil viscosity on logarithmic coordinates.

The Labedi correlation for undersaturated oil viscosity

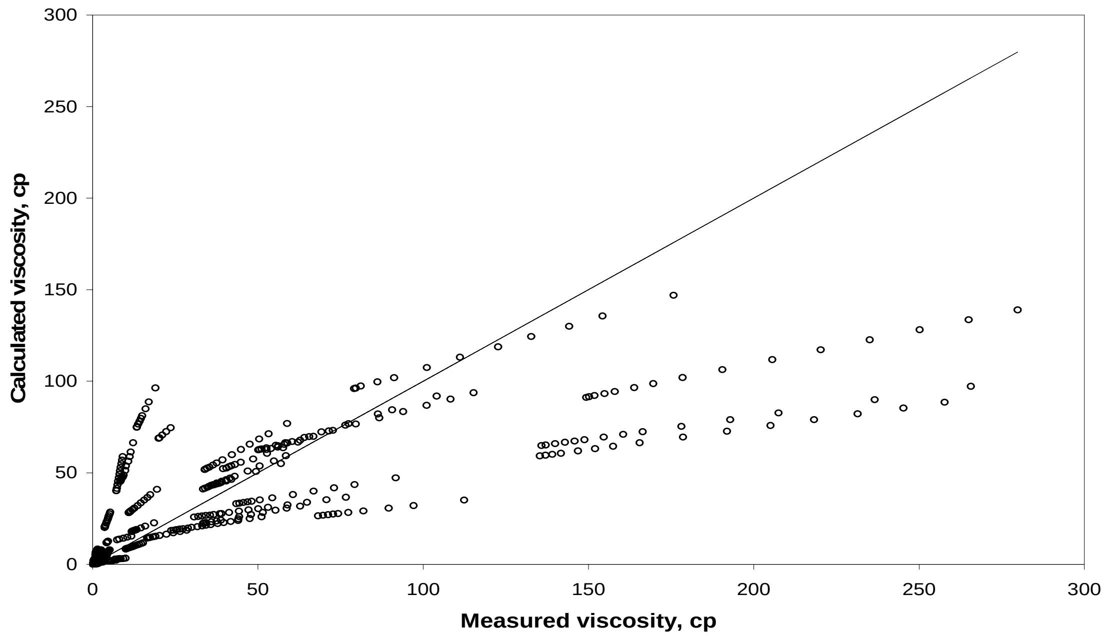

Fig. B.31- Graphical interpretation of the Labedi correlation for undersaturated oil viscosity on Cartesian coordinates.

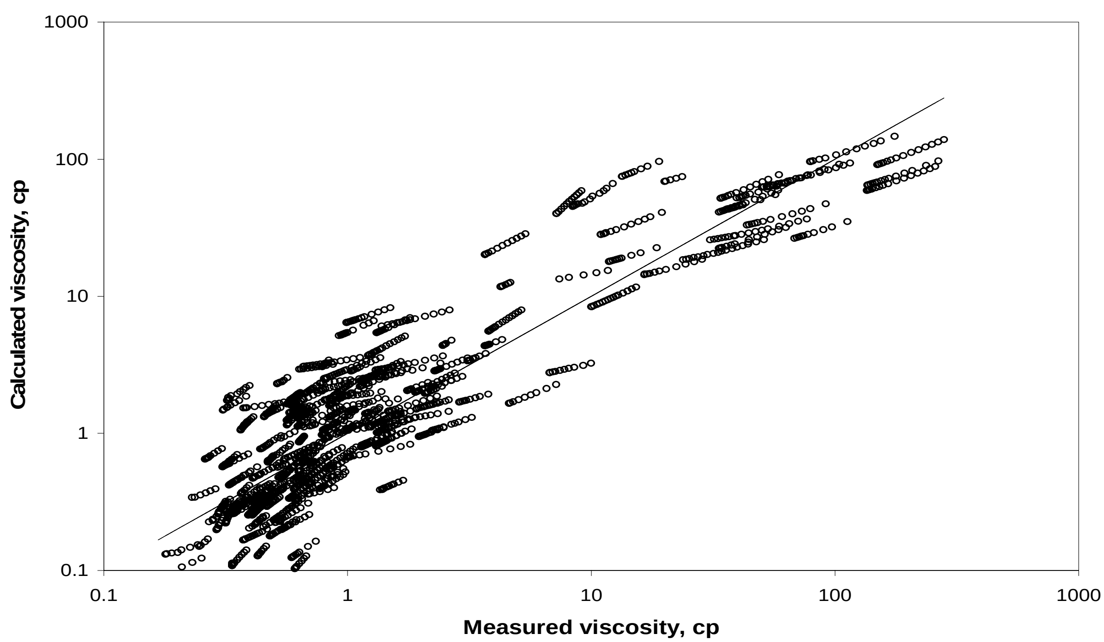

Fig. B.32- Graphical interpretation of the Labedi correlation for undersaturated oil viscosity on logarithmic coordinates.

APPENDIX C

CORRELATIONS R^2 FOR RESERVOIR OIL VISCOSITY MODEL

Saturated Oil Viscosity Correlation

Table C-1- Finding optimal correlation R^2 of transformed variables for tetravariate cases (saturated oil viscosity correlation)				
Dependent variable	**First & second stage independent variable**	**Third stage independent variable**	**Correlation R^2**	**Improvement, %**
$\ln \mu_o$	ρ_o & ρ_{sto}	γ_g	0.92	0.84
		$\ln \gamma_g$	0.92	0.82
		p	0.91	0.33
		$\ln p$	0.91	0.21
		T	0.92	0.67
		$\ln T$	0.92	0.73
		p_b	0.91	0.40
		$\ln p_b$	0.91	-0.06
		R_S	0.91	-0.37
		$\ln R_S$	0.91	0.30
		R_{Sb}	0.91	0.25
		$\ln R_{Sb}$	0.91	0.06

Exponent, *a*

Table C-2- Finding optimal correlation R^2 of transformed variables for tetravariate cases (undersaturated oil viscosity correlation)				
Dependent variable	**First & second stage independent variable**	**Third stage independent variable**	**Correlation R^2**	**Improvement, %**
$\ln a$	$\ln \rho_{ob}$ & $\ln \rho_{sto}$	T	0.747	-0.01
		$\ln T$	0.747	-0.04
		ρ_{sto}	0.747	-0.09
		$\ln \rho_{sto}$	0.747	-0.05
		γ_g	0.750	0.39
		$\ln \gamma_g$	0.750	0.33
		R_{Sb}	0.747	-0.10
		$\ln R_{Sb}$	0.745	-0.38

APPENDIX D

PERFORMANCE OF VISCOSITY CORRELATIONS FOR UNDERSATURATED RESERVOIR OIL USING LABORATORY-MEASURED BUBBLE POINT OIL VISCOSITY (183 PVT REPORTS/ 1968 DATA POINTS)

The proposed correlation for undersaturated oil viscosity

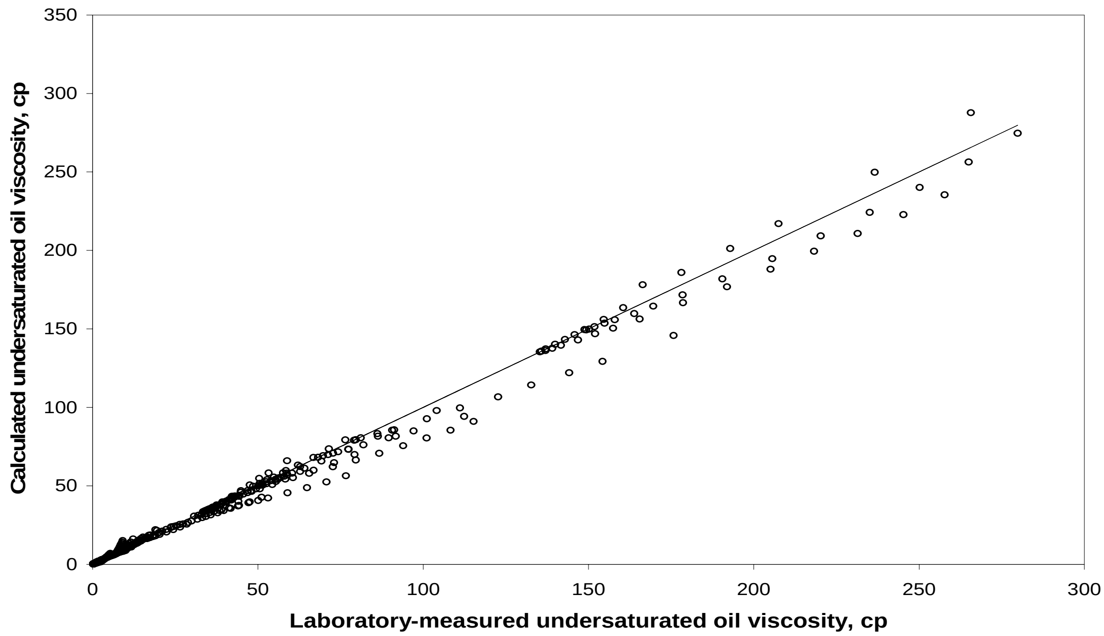

Fig. D.1- Results of the proposed correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

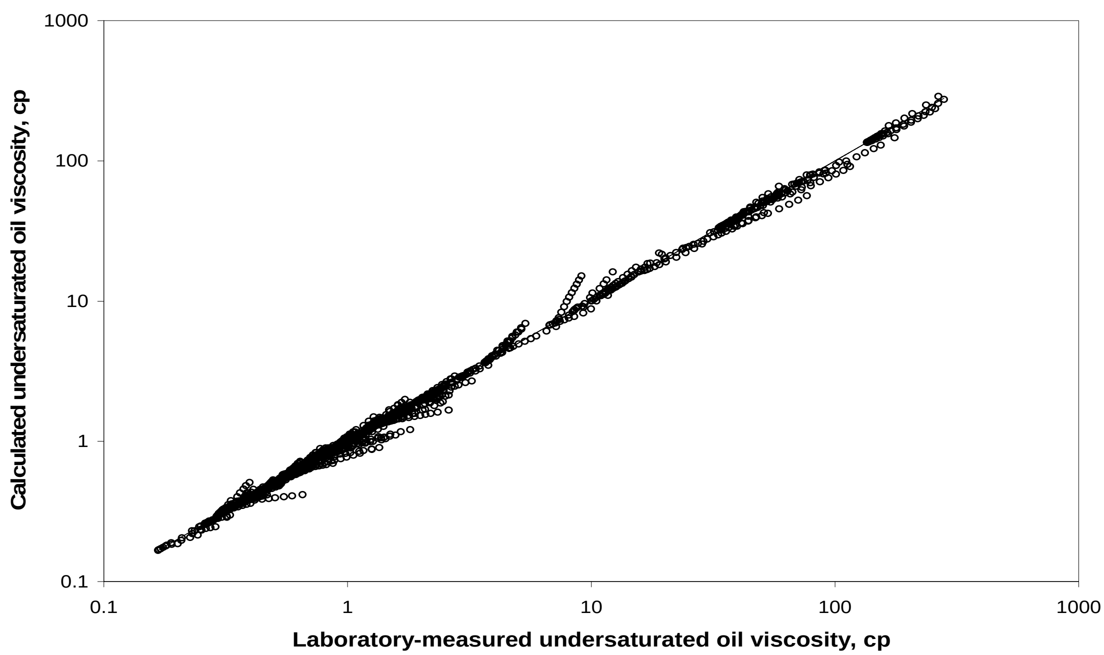

Fig. D.2- Results of the proposed correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Standing correlation for undersaturated oil viscosity

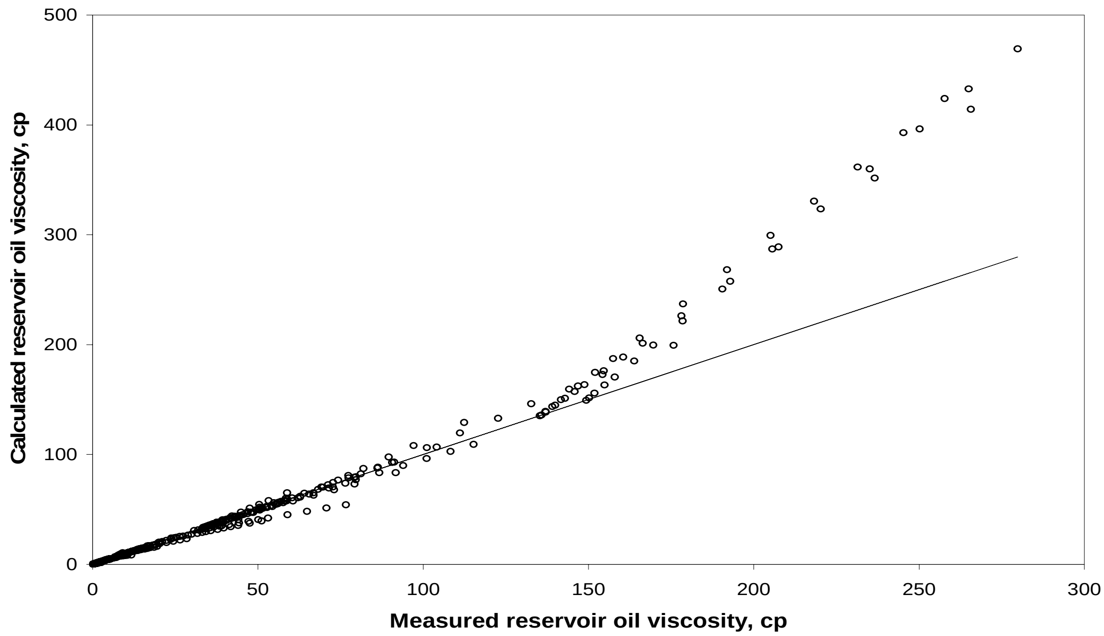

Fig. D.3- Results of the Standing correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

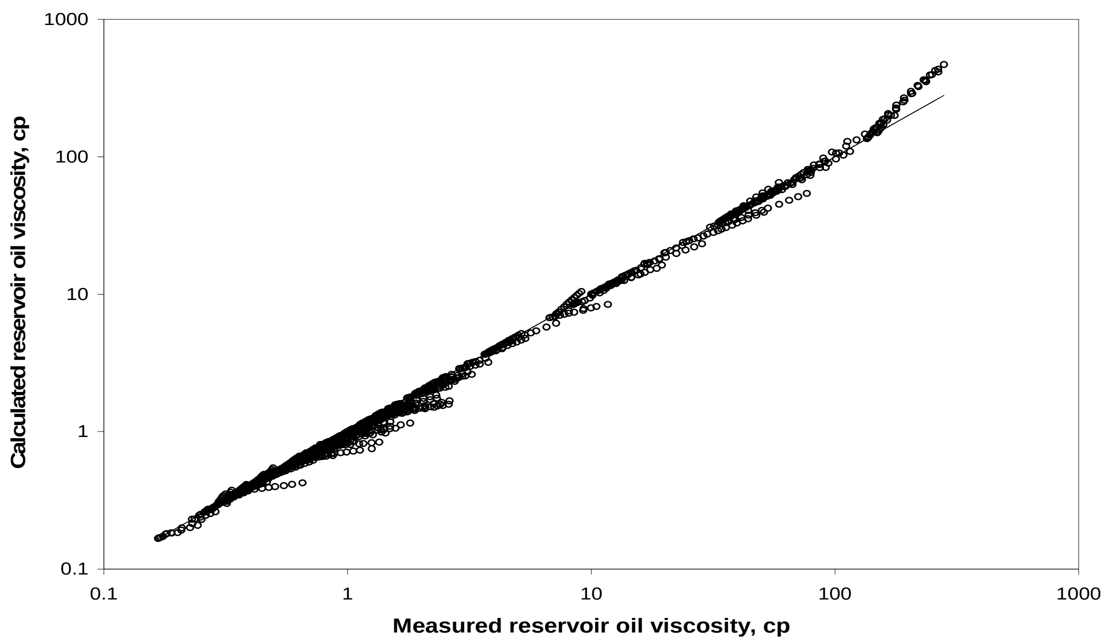

Fig. D.4- Results of the Standing correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Khan *et al.* correlation for undersaturated oil viscosity

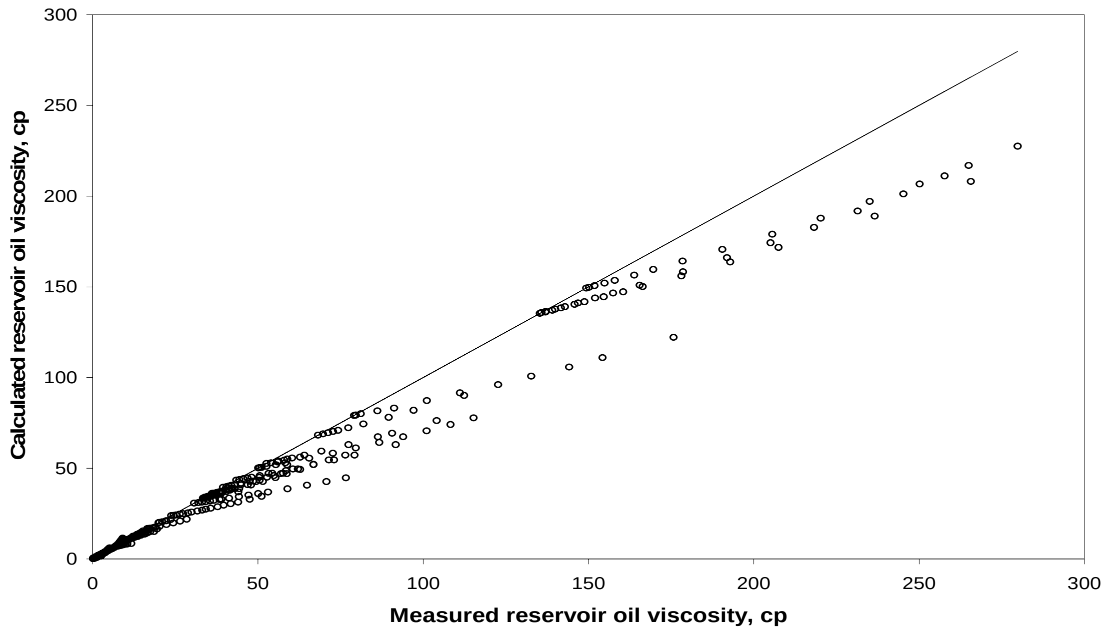

Fig. D.5- Results of the Khan *et al.* correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

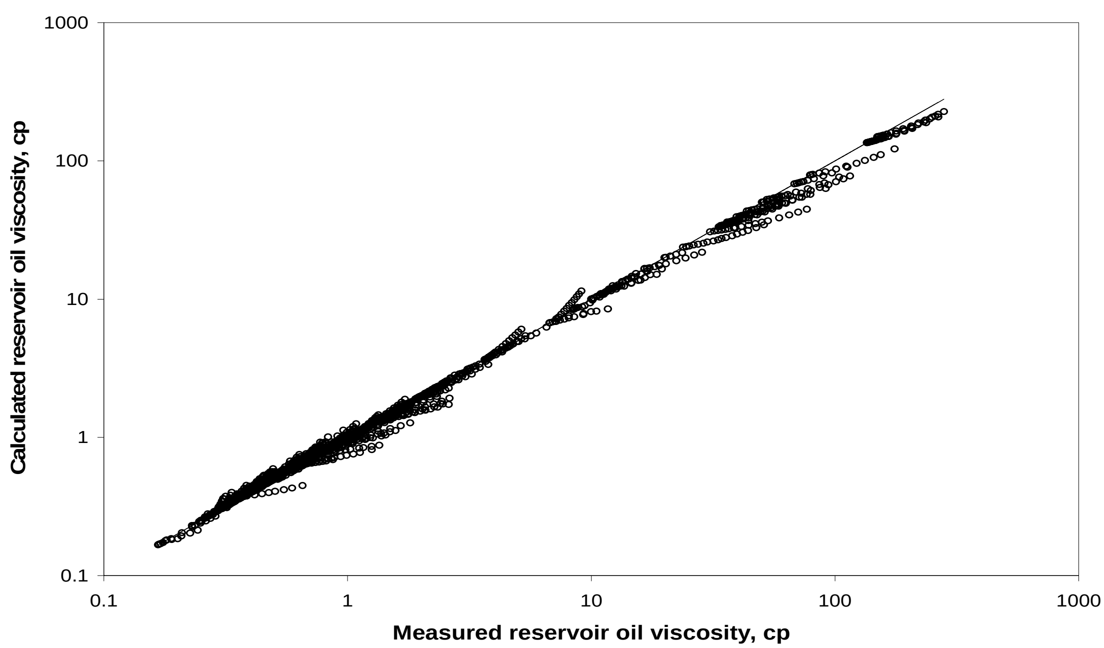

Fig. D.6- Results of the Khan *et al.* correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Almehaideb correlation for undersaturated oil viscosity

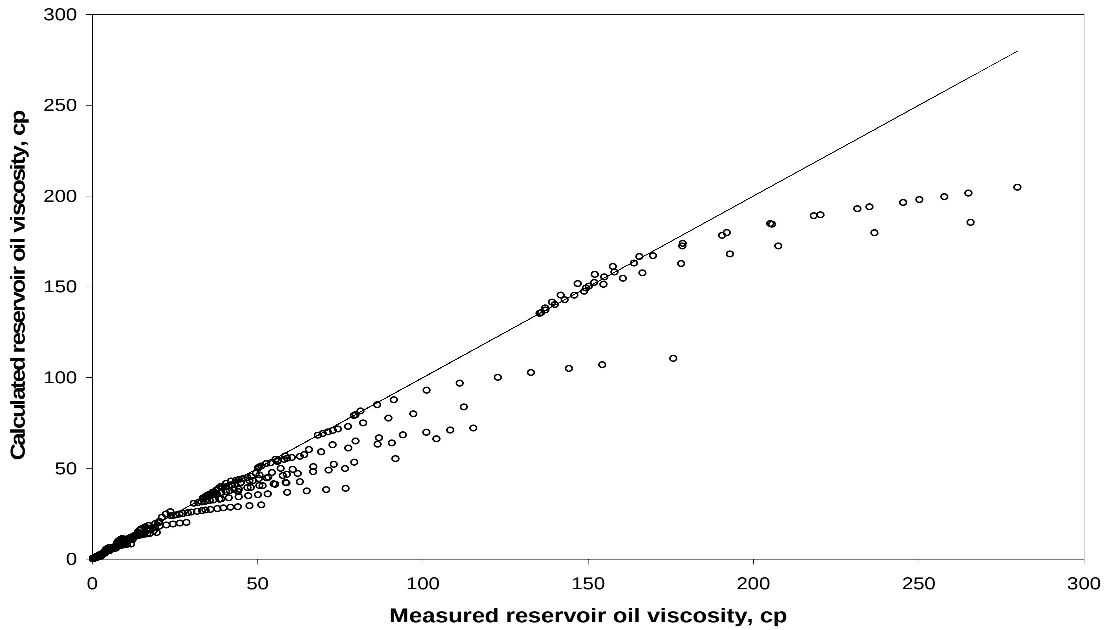

Fig. D.7- Results of the Almehaideb correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

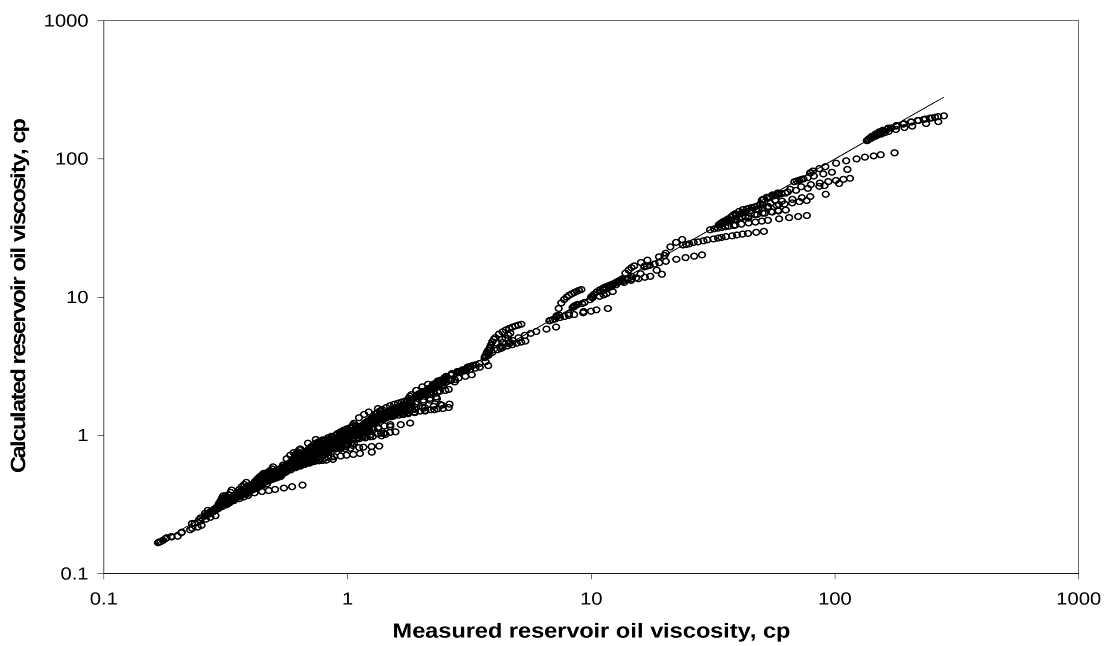

Fig. D.8- Results of the Almehaideb correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Petrosky and Farshad correlation for undersaturated oil viscosity

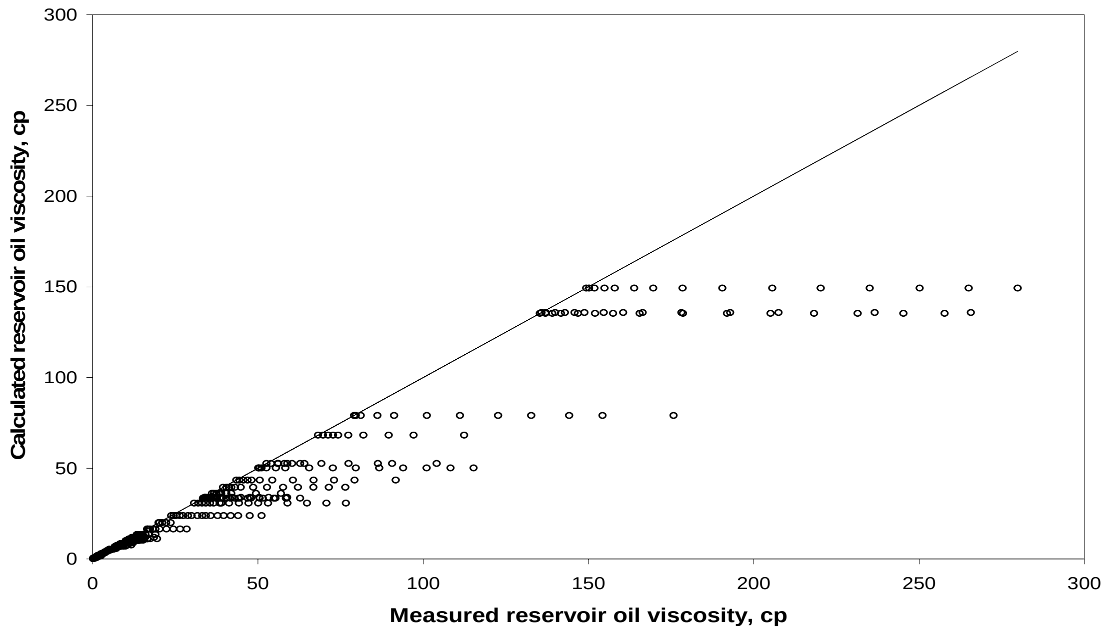

Fig. D.9- Results of the Petrosky and Farshad correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

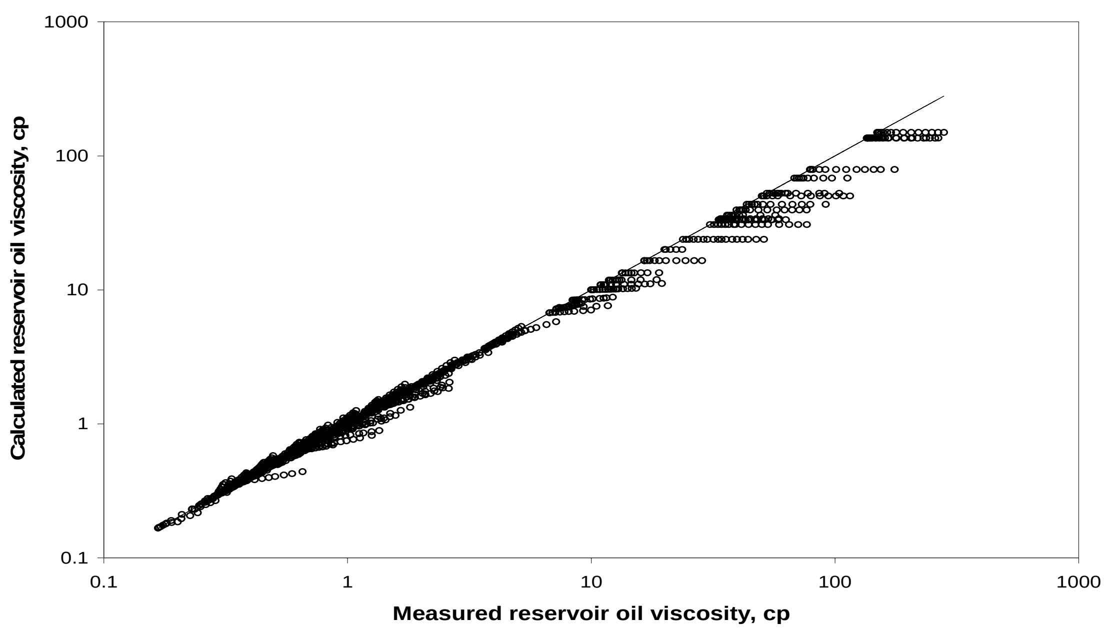

Fig. D.10- Results of the Petrosky and Farshad correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Kartoatmodjo and Schmidt correlation for undersaturated oil viscosity

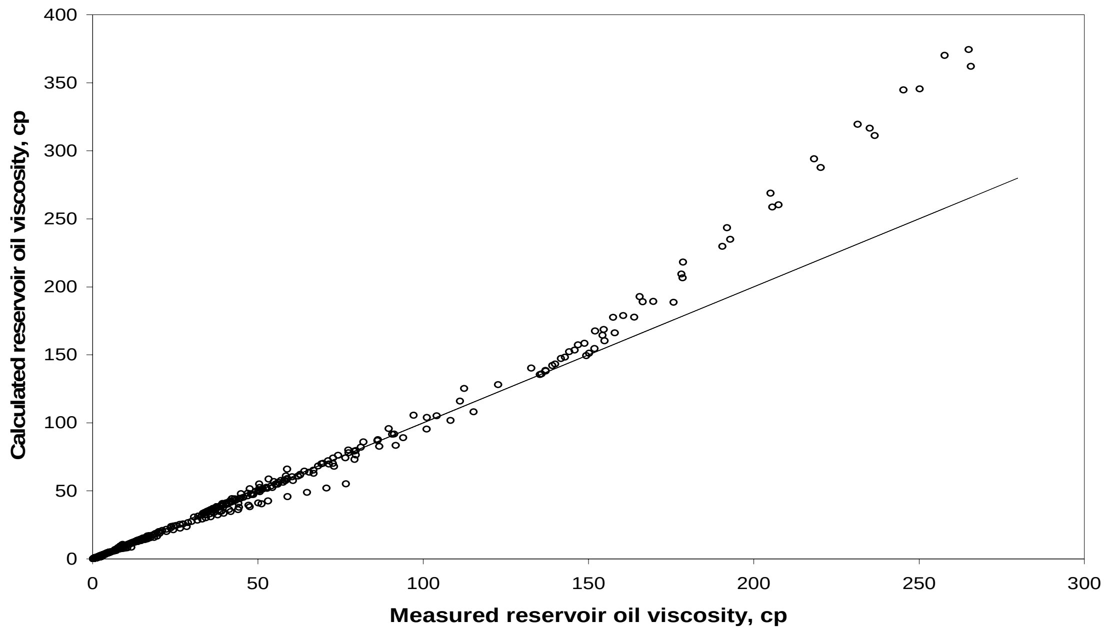

Fig. D.11- Results of the Kartoatmodjo and Schmidt correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

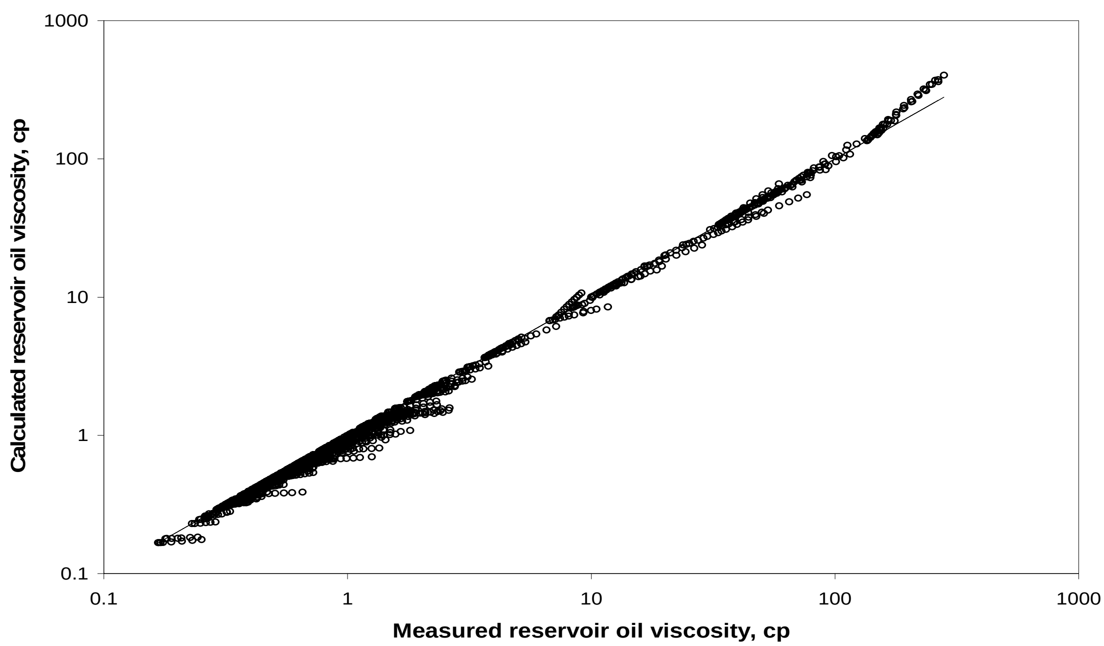

Fig. D.12- Results of the Kartoatmodjo and Schmidt correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The De Ghetto, Paone, and Villa correlation for undersaturated oil viscosity

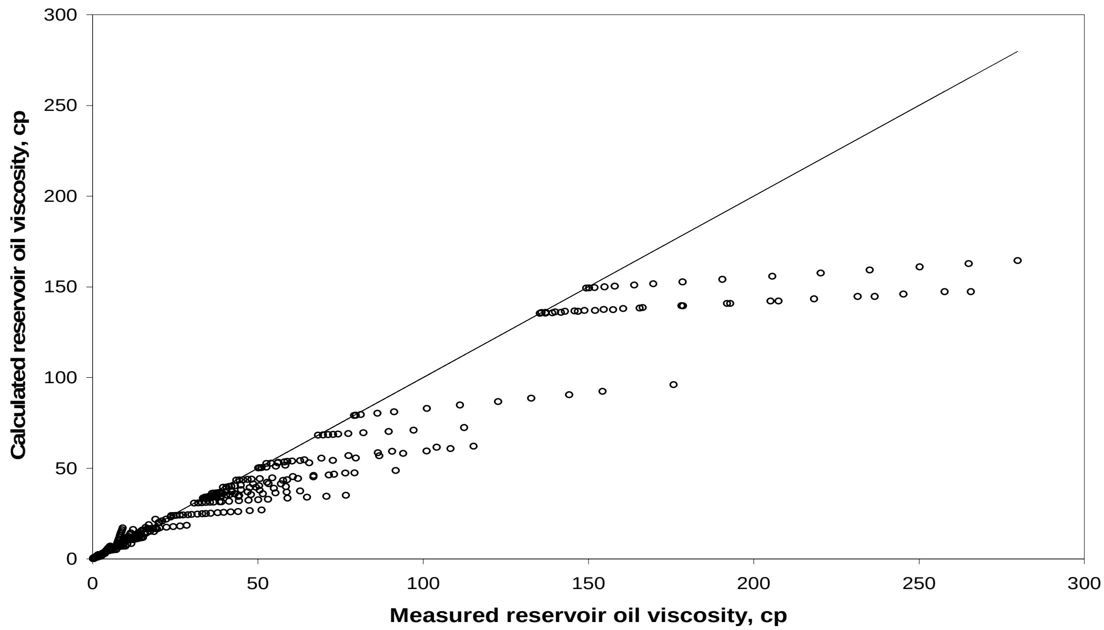

Fig. D.13- Results of the De Ghetto, Paone, and Villa correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

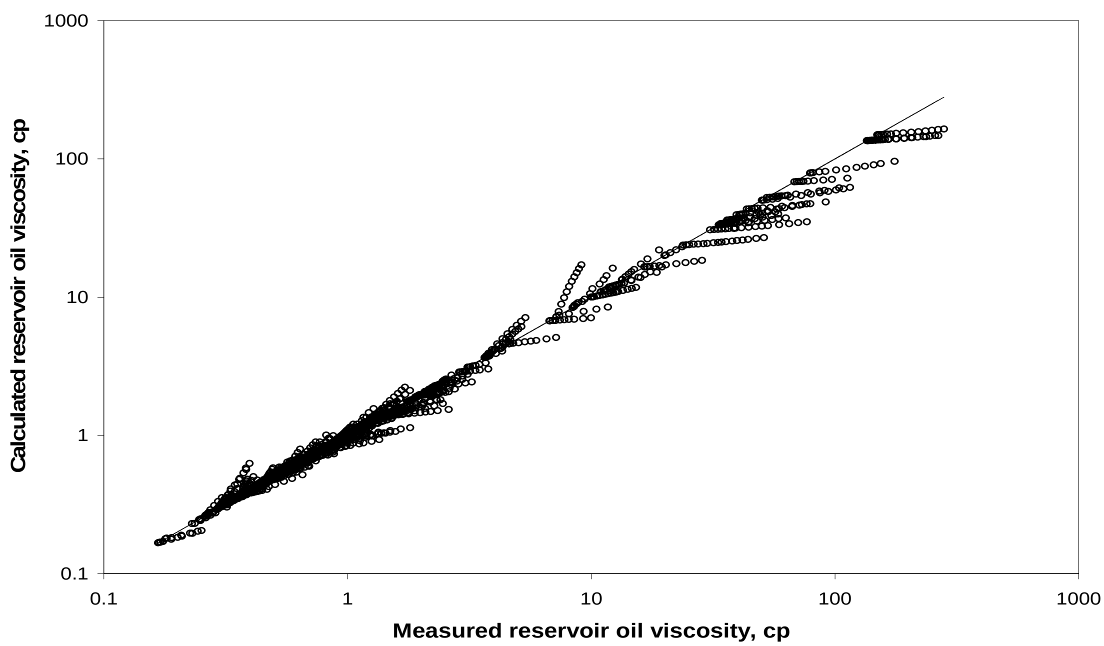

Fig. D.14- Results of the De Ghetto, Paone, and Villa correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Elsharkawy and Alikhan correlation for undersaturated oil viscosity

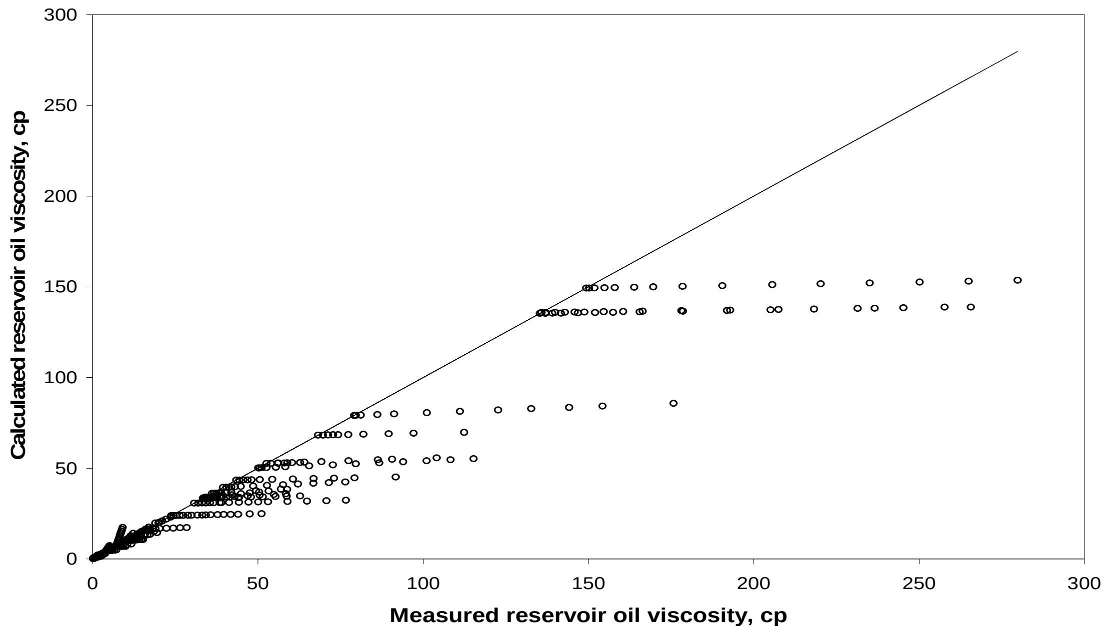

Fig. D.15- Results of the Elsharkawy and Alikhan correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

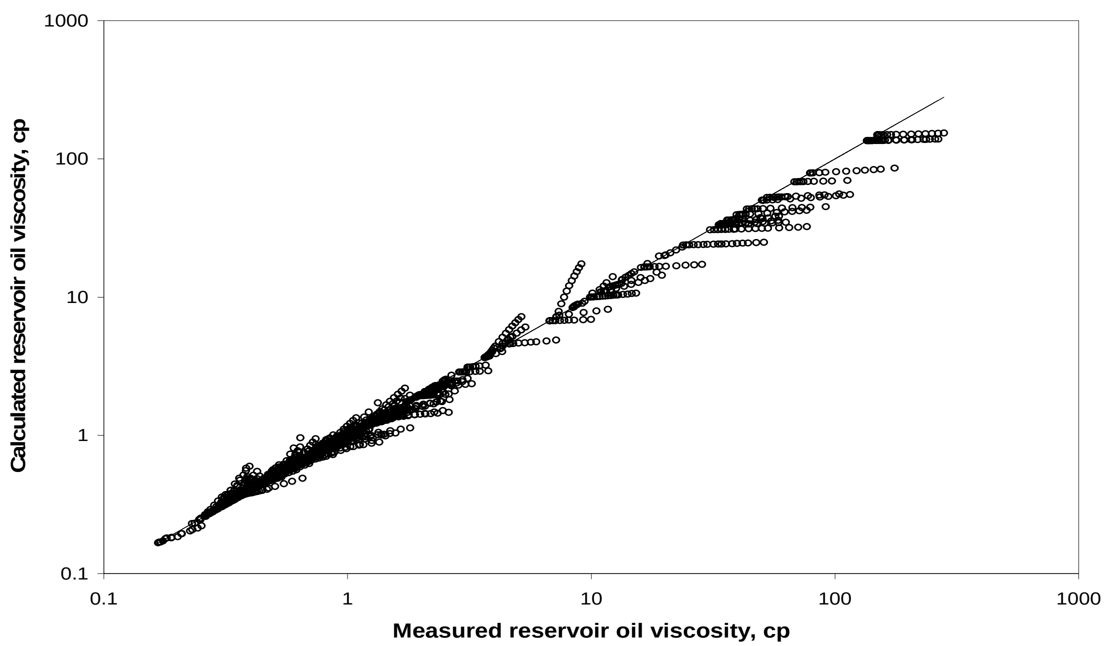

Fig. D.16- Results of the Elsharkawy and Alikhan correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Vasquez and Beggs correlation for undersaturated oil viscosity

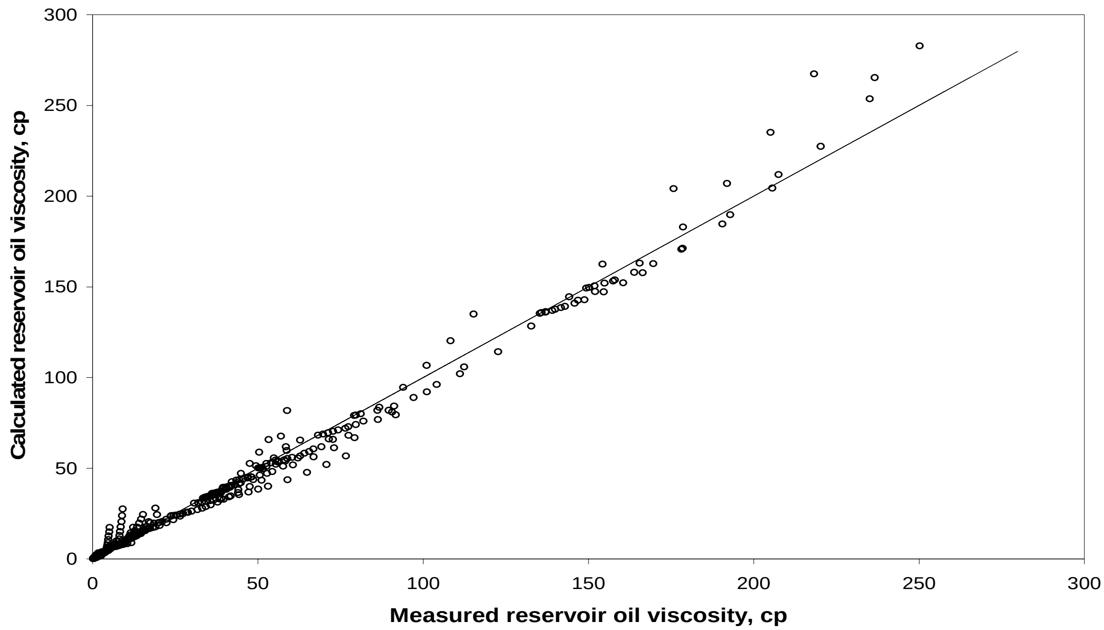

Fig. D.17- Results of the Vasquez and Beggs correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

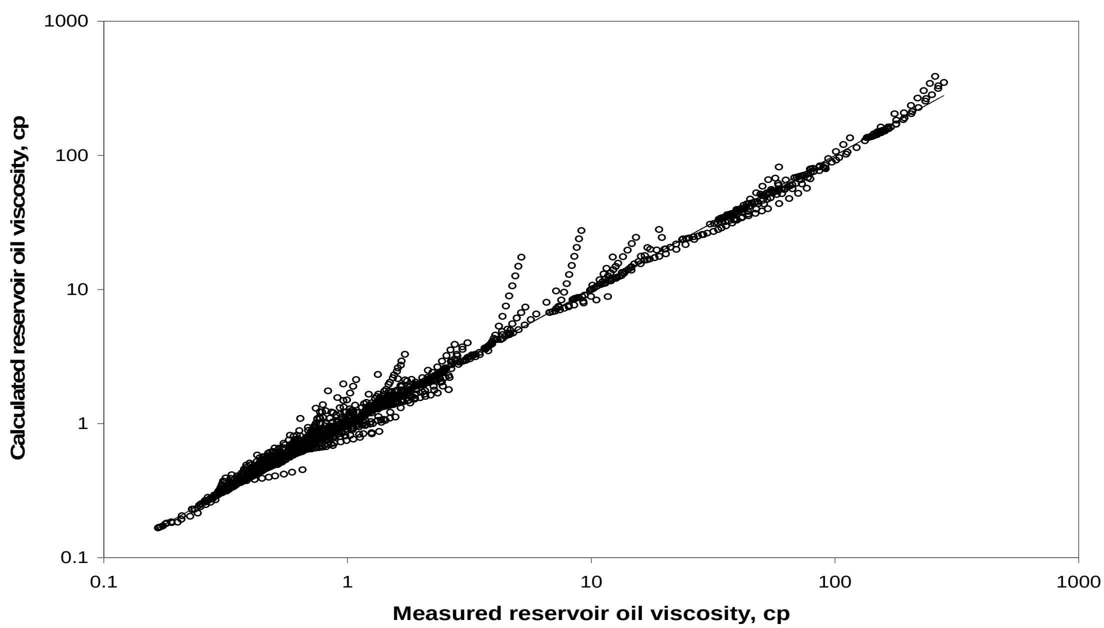

Fig. D.18- Results of the Vasquez and Beggs correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Labedi correlation for undersaturated oil viscosity

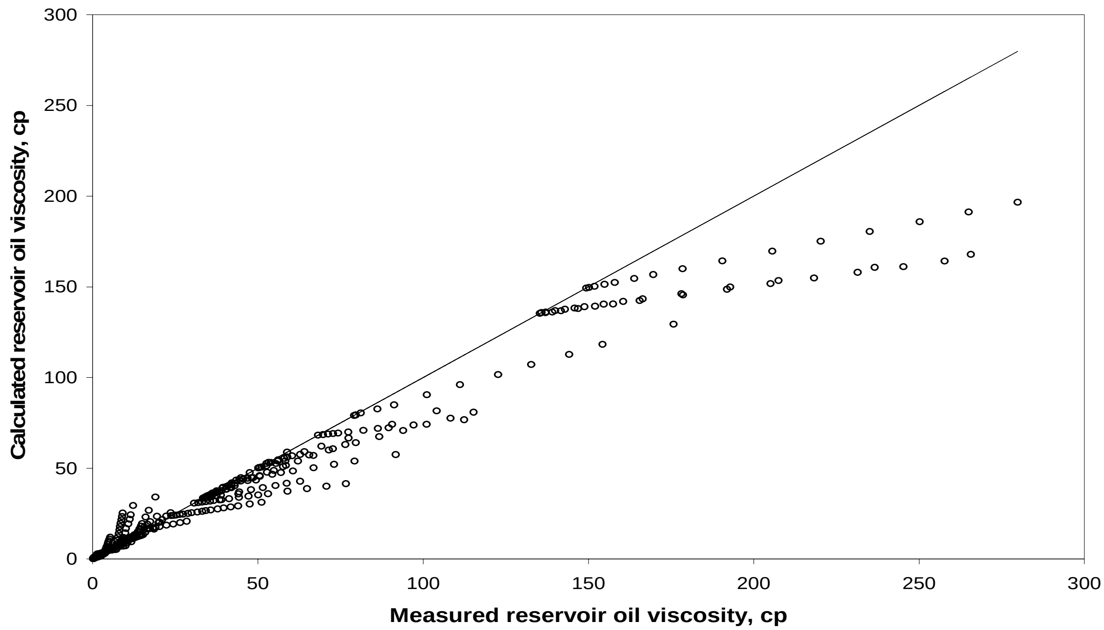

Fig. D.19- Results of the Labedi correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

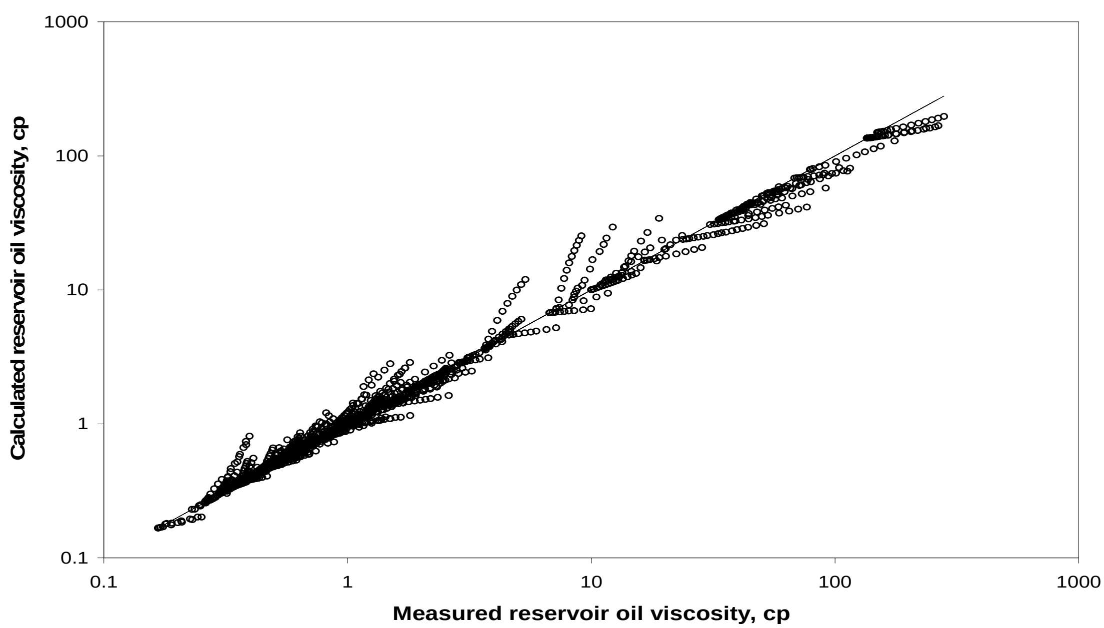

Fig. D.20- Results of the Labedi correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Elsharkwy and Gharbi correlation for undersaturated oil viscosity

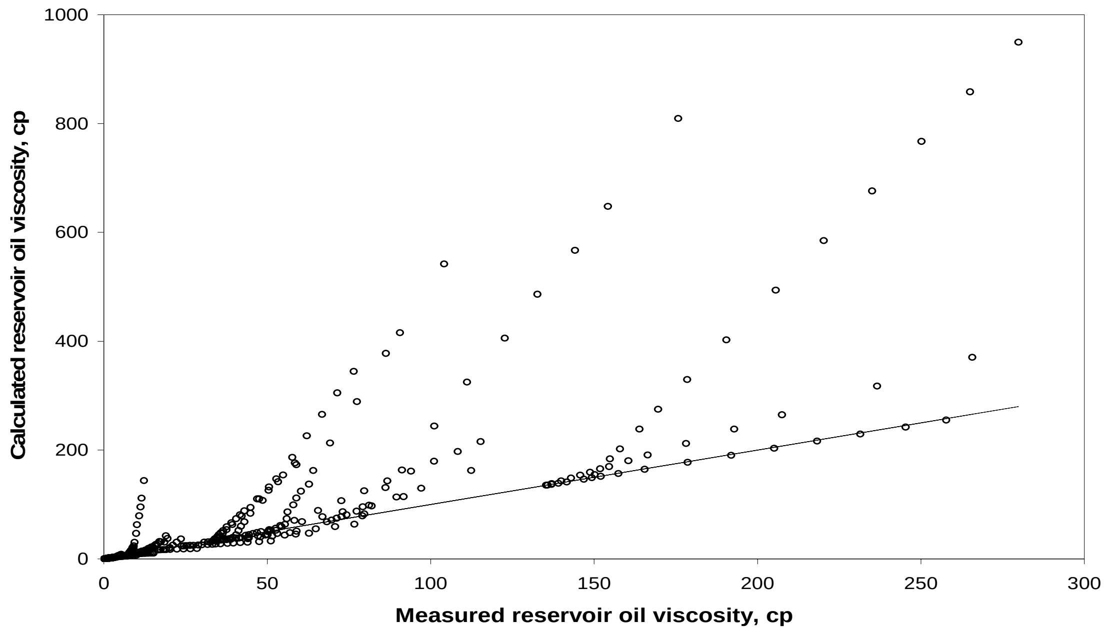

Fig. D.21- Results of the Elsharkwy and Gharbi correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

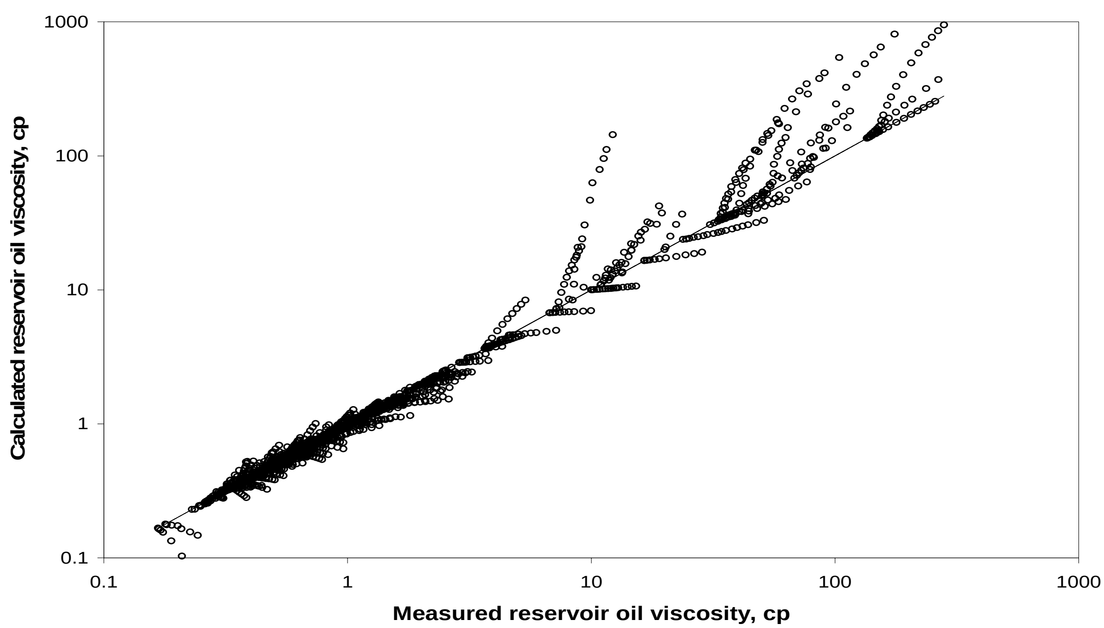

Fig. D.22- Results of the Elsharkwy and Gharbi correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Al-Khafaji, Abdul-Majeed, and Hassoon correlation for undersaturated oil viscosity

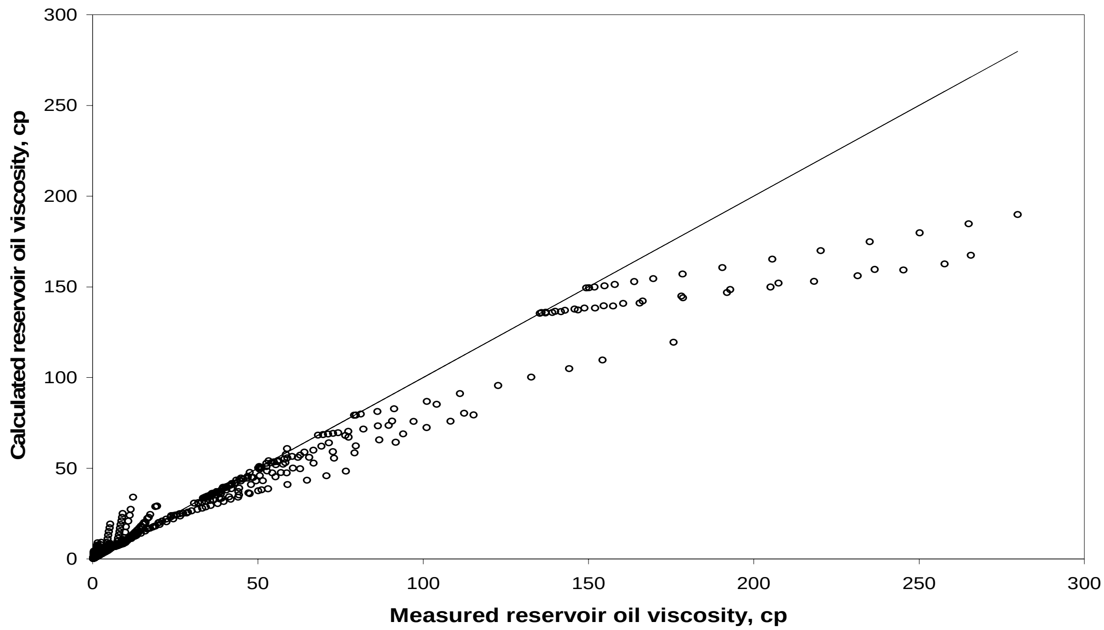

Fig. D.23- Results of the Al-Khafaji *et al* correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

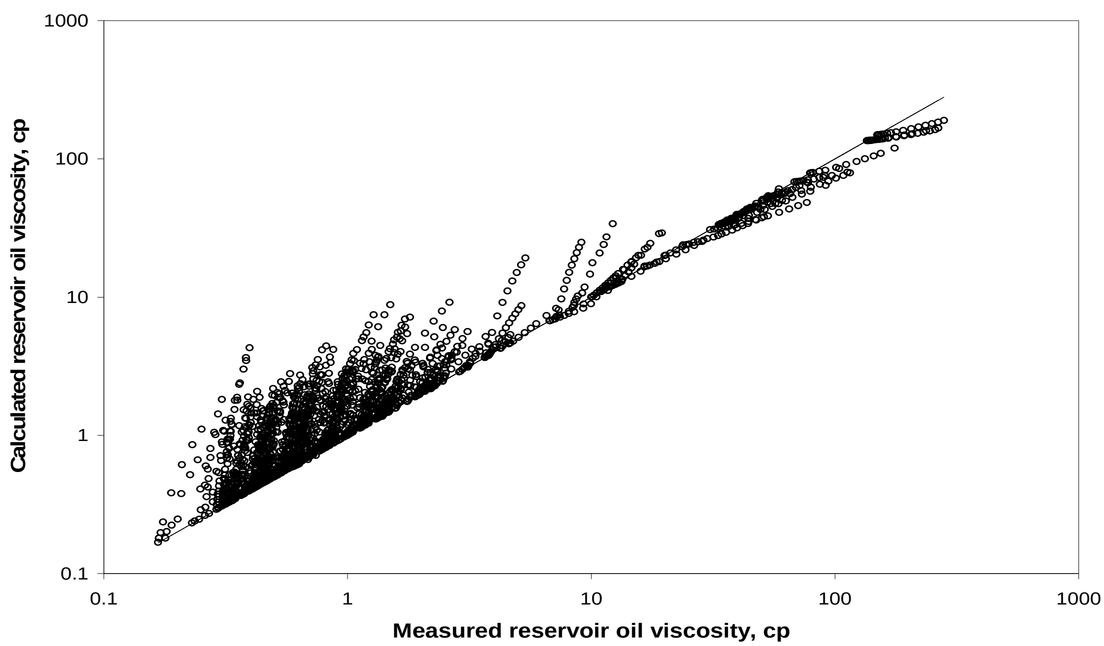

Fig. D.24- Results of the Al-Khafaji *et al* correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

The Dindoruk and Christman correlation for undersaturated oil viscosity

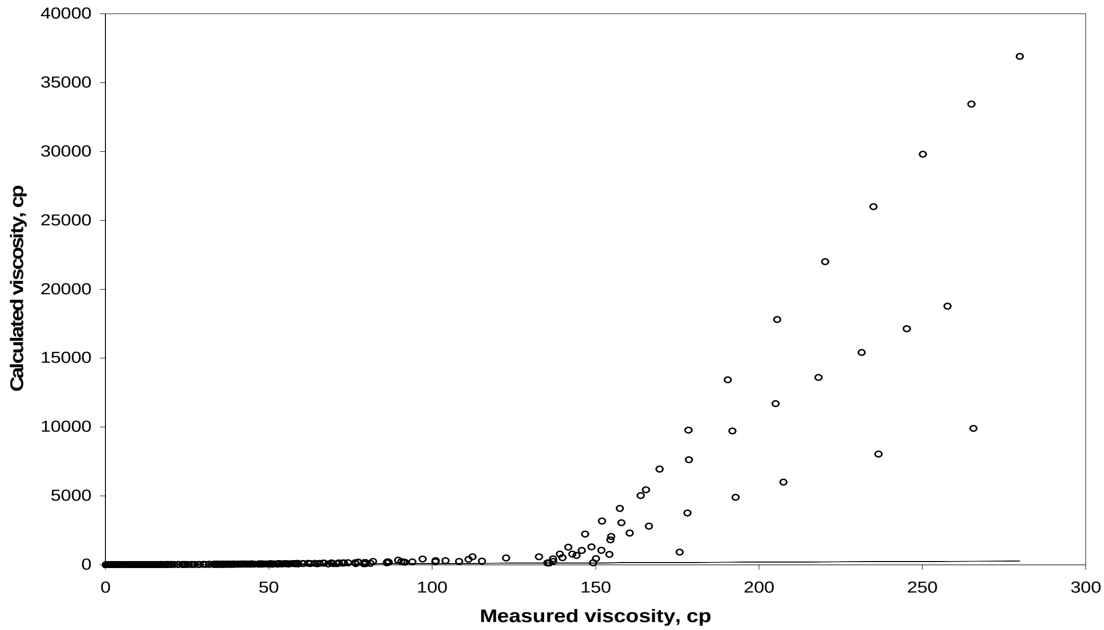

Fig. D.25- Results of the Dindoruk and Christman correlation for undersaturated oil viscosity on Cartesian scales using laboratory-measured bubble point oil viscosity.

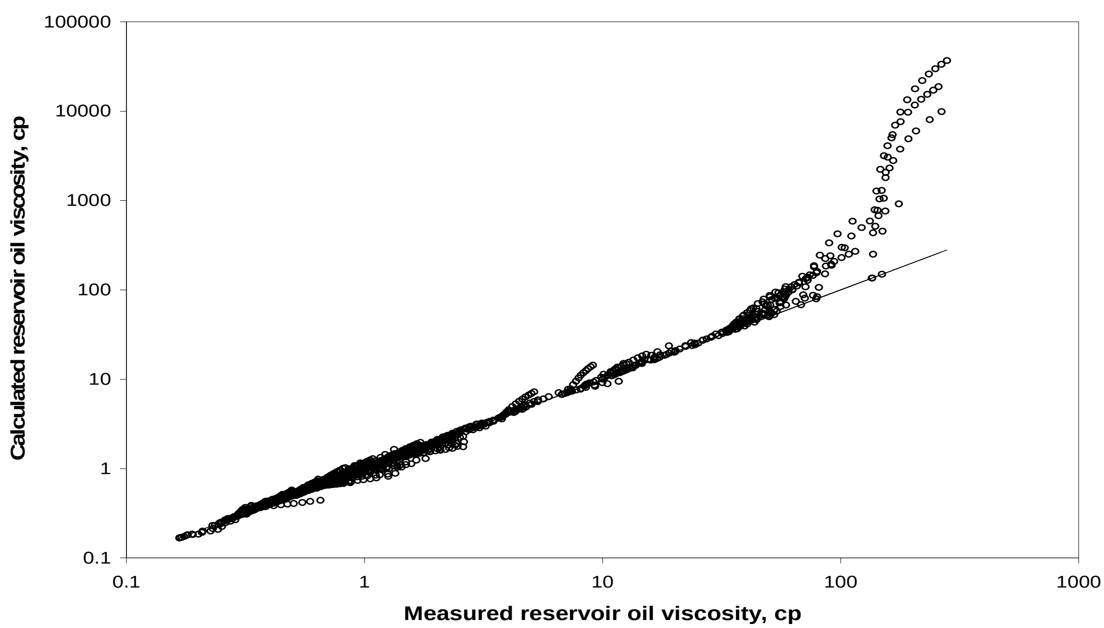

Fig. D.26- Results of the Dindoruk and Christman correlation for undersaturated oil viscosity on logarithmic scales using laboratory-measured bubble point oil viscosity.

APPENDIX E

STATISTICAL ERROR ANALYSIS RESULTS OF THE PROPOSED OIL VISCOSITY CORRELATIONS AT ANY RESERVOIR CONDITIONS

Table E-1- A comparison of ARE in percentage obtained from saturated oil viscosity correlation equations regarding stock-tank oil gravity								
Published correlations	**Stock-tank oil gravity, ^{o}API**							
	<=20	**20-25**	**25-30**	**30-35**	**35-40**	**40-45**	**45-50**	**>50**
This work	-19.3	-8.8	0.3	-7.3	-3.4	9.0	3.3	5.8
Beggs and Robinson	-71.0	-20.3	2.4	-7.4	-2.0	0.2	-10.0	10.4
De Ghetto, Paone, and Villa	-46.6	25.0	17.8	-3.6	4.3	3.4	-6.7	5.7
Dindoruk and Christman	-57.7	-10.1	22.8	-4.0	-12.8	-17.8	-30.5	-40.6
Petrosky and Farshad	-56.5	-1.3	28.9	7.6	-2.0	-3.3	-15.3	-30.3

Table E-2- A comparison of AARE in percentage obtained from saturated oil viscosity correlation equations regarding stock-tank oil gravity								
Published correlations	**Stock-tank oil gravity, ^{o}API**							
	<=20	**20-25**	**25-30**	**30-35**	**35-40**	**40-45**	**45-50**	**>50**
This work	48.1	38.5	22.5	31.3	23.4	19.5	12.1	5.8
Beggs and Robinson	72.1	39.5	26.1	29.1	27.1	18.2	19.1	10.4
De Ghetto, Paone, and Villa	57.3	60.1	34.0	30.6	26.7	18.2	17.8	5.7
Dindoruk and Christman	60.0	37.6	36.7	30.5	23.6	21.5	31.4	40.6
Petrosky and Farshad	58.4	47.2	40.6	36.6	25.0	17.1	18.4	30.3

Table E-3- A comparison of ARE in percentage obtained from saturated oil viscosity correlation equations regarding reservoir temperature									
Published correlations	**Reservoir temperature, ^oF**								
	100-125	**126-150**	**151-175**	**176-200**	**201-225**	**226-250**	**251-275**	**276-300**	**>300**
This work	1.8	5.9	-4.5	-4.2	6.4	-2.4	-2.4	-14.0	-11.7
Beggs and Robinson	24.2	24.0	-9.8	-5.5	-4.5	-14.8	-16.2	-31.1	-25.2
De Ghetto, Paone, and Villa	-4.0	10.1	-0.8	2.4	5.2	-4.3	5.9	-14.5	19.9
Dindoruk and Christman	-16.8	-2.4	-13.9	-2.4	-9.3	-18.4	-11.0	-34.5	-31.9
Petrosky and Farshad	-7.4	1.9	-7.0	5.3	5.0	-2.1	6.6	-15.4	-28.1

Table E-4- A comparison of AARE in percentage obtained from saturated oil viscosity correlation equations regarding reservoir temperature									
Published correlations	**Reservoir temperature, ^oF**								
	100-125	**126-150**	**151-175**	**176-200**	**201-225**	**226-250**	**251-275**	**276-300**	**>300**
This work	7.3	16.8	30.9	28.6	19.5	29.8	21.8	22.6	11.7
Beggs and Robinson	24.2	26.0	39.4	28.8	16.9	27.1	21.3	33.2	25.2
De Ghetto, Paone, and Villa	7.0	19.9	36.1	33.9	21.5	29.2	24.1	28.0	19.9
Dindoruk and Christman	19.0	19.0	33.5	34.3	21.6	33.7	26.5	37.6	31.9
Petrosky and Farshad	7.7	14.5	35.7	34.0	22.3	34.6	34.3	31.4	28.1

Table E-5- A comparison of ARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point solution gas-oil ratio								
Published correlations	**Bubble point solution gas-oil ratio, scf/STB**							
	<=200	**201-400**	**401-600**	**601-800**	**801-1000**	**1001-1200**	**1201-1400**	**>1400**
This work	-21.1	-4.3	1.7	10.2	2.1	6.7	10.0	-2.8
Beggs and Robinson	-33.7	3.1	-3.8	5.0	-9.3	-6.9	-9.2	-12.5
De Ghetto, Paone, and Villa	-14.7	10.1	3.4	12.6	-6.6	0.3	-6.4	-11.3
Dindoruk and Christman	-33.8	-3.5	-9.0	9.8	-21.0	-8.7	-28.7	-24.7
Petrosky and Farshad	-29.5	6.6	5.3	20.6	-6.6	4.7	-10.2	-12.6

Table E-6- A comparison of AARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point solution gas-oil ratio								
Published correlations	**Bubble point solution gas-oil ratio, scf/STB**							
	<=200	**201-400**	**401-600**	**601-800**	**801-1000**	**1001-1200**	**1201-1400**	**>1400**
This work	41.3	26.5	23.7	22.8	18.4	16.8	14.1	9.7
Beggs and Robinson	49.8	30.7	22.8	21.4	19.1	15.5	11.7	16.3
De Ghetto, Paone, and Villa	45.6	31.8	26.7	26.6	19.7	18.3	9.1	13.1
Dindoruk and Christman	45.6	28.5	27.5	26.8	22.7	21.1	28.7	26.6
Petrosky and Farshad	46.6	31.1	29.6	31.5	16.0	20.6	10.8	16.6

Table E-7- A comparison of ARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point oil viscosity less than 1 cp									
Published correlations	**Bubble point oil viscosity, cp**								
	0.1-0.2	**0.2-0.3**	**0.3-0.4**	**0.4-0.5**	**0.5-0.6**	**0.6-0.7**	**0.7-0.8**	**0.8-0.9**	**0.9-1.0**
This work	1.3	20.8	26.7	5.2	0.8	0.9	3.5	-10.5	-6.7
Beggs and Robinson	-13.4	5.5	11.9	-5.8	-3.1	0.5	12.6	0.8	-7.8
De Ghetto, Paone, and Villa	-7.5	8.0	19.2	0.2	3.8	12.4	24.6	-1.2	7.9
Dindoruk and Christman	-32.0	-10.6	-0.2	-14.9	-5.8	0.7	18.7	-5.0	6.1
Petrosky and Farshad	-15.1	7.4	18.3	-1.7	8.9	10.9	21.4	2.3	18.8

Table E-8- A comparison of AARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point oil viscosity less than 1 cp									
Published correlations	**Bubble point oil viscosity, cp**								
	0.1-0.2	**0.2-0.3**	**0.3-0.4**	**0.4-0.5**	**0.5-0.6**	**0.6-0.7**	**0.7-0.8**	**0.8-0.9**	**0.9-1.0**
This work	10.2	23.4	28.4	12.6	15.0	13.5	16.2	19.5	16.5
Beggs and Robinson	17.3	12.2	21.1	16.5	18.0	15.9	28.3	28.2	18.8
De Ghetto, Paone, and Villa	9.8	15.6	26.1	17.5	21.6	23.1	28.4	25.6	29.2
Dindoruk and Christman	32.0	14.9	20.4	22.1	23.3	24.8	33.2	25.3	19.4
Petrosky and Farshad	15.8	15.4	25.8	17.3	26.8	26.9	34.3	24.0	30.1

Table E-9- A comparison of ARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point oil viscosity between 1 to 10 cp					
Published correlations	**Bubble point oil viscosity, cp**				
	1-2	**2-3**	**3-4**	**4-5**	**7-8**
This work	-27.1	-45.8	-22.6	-4.7	10.5
Beggs and Robinson	-19.6	-37.7	-32.2	64.4	15.6
De Ghetto, Paone, and Villa	-13.3	-39.5	15.0	4.7	25.2
Dindoruk and Christman	-19.9	-41.7	-14.1	16.0	11.8
Petrosky and Farshad	-12.1	-39.6	-4.4	11.0	0.8

Table E-10- A comparison of AARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point oil viscosity between 1 to 10 cp					
Published correlations	**Bubble point oil viscosity, cp**				
	1-2	**2-3**	**3-4**	**4-5**	**7-8**
This work	34.0	46.5	60.7	4.7	10.5
Beggs and Robinson	33.1	50.6	43.0	64.4	15.6
De Ghetto, Paone, and Villa	32.0	39.5	85.9	4.7	25.2
Dindoruk and Christman	35.4	47.0	54.1	16.0	11.8
Petrosky and Farshad	34.5	42.3	60.8	11.0	4.2

Table E-11- A comparison of ARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point oil viscosity greater than 10 cp								
Published correlations	**Bubble point oil viscosity, cp**							
	10-20	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**131-140**	**141-150**
This work	2.0	-69.9	-37.8	-67.3	-14.9	-72.2	-64.0	-39.5
Beggs and Robinson	-27.2	-78.2	-75.7	-83.7	-80.2	-79.6	-90.3	-90.6
De Ghetto, Paone, and Villa	1.1	-51.3	-49.9	-63.3	-57.4	-65.1	-81.2	-80.2
Dindoruk and Christman	-26.2	-69.2	-61.9	-72.3	-61.7	-76.4	-84.3	-80.2
Petrosky and Farshad	-25.8	-67.2	-60.0	-71.8	-59.6	-79.9	-82.7	-79.0

Table E-12- A comparison of AARE in percentage obtained from saturated oil viscosity correlation equations regarding bubble point oil viscosity greater than 10 cp								
Published correlations	**Bubble point oil viscosity, cp**							
	10-20	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**131-140**	**141-150**
This work	64.2	69.9	38.8	67.3	18.5	72.2	64.0	39.5
Beggs and Robinson	45.9	78.2	75.7	83.7	80.2	79.6	90.3	90.6
De Ghetto, Paone, and Villa	45.2	51.3	49.9	63.3	57.4	65.1	81.2	80.2
Dindoruk and Christman	34.6	69.2	61.9	72.3	61.7	76.4	84.3	80.2
Petrosky and Farshad	32.9	67.2	60.0	71.8	59.6	79.9	82.7	79.0

Table E-13- A comparison of ARE in percentage obtained from undersaturated oil viscosity correlation equations regarding stock-tank oil gravity								
Published correlations	Stock-tank oil gravity, ^oAPI							
	<=20	20-25	25-30	30-35	35-40	40-45	45-50	>50
This work	-28.1	-8.6	-14.6	-11.1	-8.5	4.4	-5.1	5.8
Dindoruk and Christman	-57.4	-10.5	1.3	-11.2	-18.6	-23.7	-32.1	-38.1
Petrosky and Farshad	-65.7	-14.9	7.1	0.2	-7.6	-8.7	-16.0	-30.0
Vasquez and Beggs	-75.9	-21.0	-18.7	-9.2	-6.9	-1.4	-2.6	26.5
De Ghetto, Paone, and Villa	-82.1	-24.1	8.9	4.9	-6.0	-10.3	-22.3	-46.4

Table E-14- A comparison of AARE in percentage obtained from undersaturated oil viscosity correlations regarding stock-tank oil gravity								
Published correlations	Stock-tank oil gravity, ^oAPI							
	<=20	20-25	25-30	30-35	35-40	40-45	45-50	>50
This work	55.4	52.5	25.2	33.4	26.5	17.0	18.4	5.8
Dindoruk and Christman	61.3	47.9	29.5	30.9	26.7	25.5	35.1	38.1
Petrosky and Farshad	68.3	52.0	32.0	36.3	27.6	19.4	21.3	30.0
Vasquez and Beggs	76.4	58.2	27.7	34.4	29.0	22.0	26.9	26.5
De Ghetto, Paone, and Villa	82.1	57.2	33.8	39.3	26.7	18.6	24.9	46.4

Table E-15- A comparison of ARE in percentage obtained from undersaturated oil viscosity correlation equations regarding reservoir temperature									
Published correlations	Reservoir temperature, ^{o}F								
	100-125	126-150	151-175	176-200	201-225	226-250	251-275	276-300	>300
This work	6.1	5.9	-7.8	-14.6	1.0	-14.1	-3.3	-19.1	-7.6
Dindoruk and Christman	-14.2	-0.4	-22.3	-15.0	-15.9	-25.2	-16.5	-33.0	-25.5
Petrosky and Farshad	-16.7	2.8	-24.7	-8.3	-1.6	-10.6	0.2	-9.7	-23.5
Vasquez and Beggs	37.2	43.4	-29.0	-17.5	-7.1	-18.8	-16.9	-32.0	-14.0
De Ghetto, Paone, and Villa	-34.2	-6.8	-35.4	-8.7	-0.7	-4.8	6.3	-3.7	-6.9

Table E-16- A comparison of AARE in percentage obtained from undersaturated oil viscosity correlation equations regarding reservoir temperature									
Published correlations	Reservoir temperature, ^{o}F								
	100-125	126-150	151-175	176-200	201-225	226-250	251-275	276-300	>300
This work	6.1	19.0	46.7	32.5	20.7	35.9	18.9	24.8	7.6
Dindoruk and Christman	17.9	15.7	46.1	34.4	25.1	39.0	22.8	36.1	25.5
Petrosky and Farshad	18.6	16.9	46.9	33.2	23.3	41.2	26.3	35.8	23.5
Vasquez and Beggs	37.2	46.1	50.0	30.8	21.6	36.0	22.1	34.0	17.6
De Ghetto, Paone, and Villa	34.2	17.1	49.8	34.1	24.8	43.9	26.4	37.2	6.9

Table E-17- A comparison of ARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point solution gas-oil ratio								
Published correlations	Bubble point solution gas-oil ratio, scf/STB							
	<=200	201-400	401-600	601-800	801-1000	1001-1200	1201-1400	>1400
This work	-16.3	-6.8	4.9	0.4	-2.7	-5.9	-4.6	-25.6
Dindoruk and Christman	-29.1	-8.8	-12.6	-5.3	-28.8	-22.3	-30.8	-25.4
Petrosky and Farshad	-31.9	4.9	4.4	4.6	-13.7	-11.1	-14.1	-28.1
Vasquez and Beggs	-25.7	-7.1	-6.7	-7.7	-14.5	-14.9	-6.9	-26.8
De Ghetto, Paone, and Villa	-39.4	7.7	7.6	5.0	-15.7	-14.6	-19.7	-36.9

Table E-18- A comparison of AARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point solution gas-oil ratio								
Published correlations	Bubble point solution gas-oil ratio, scf/STB							
	<=200	201-400	401-600	601-800	801-1000	1001-1200	1201-1400	>1400
This work	48.2	26.4	25.3	25.5	14.8	19.4	10.7	25.6
Dindoruk and Christman	47.2	28.3	25.8	26.2	28.8	26.5	30.8	25.4
Petrosky and Farshad	49.0	32.6	27.6	27.4	17.0	21.1	14.1	28.1
Vasquez and Beggs	56.6	27.2	24.3	25.4	20.8	24.3	10.8	26.8
De Ghetto, Paone, and Villa	50.9	33.8	30.3	29.2	18.0	23.1	19.7	36.9

Table E-19- A comparison of ARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point oil viscosity less than 1 cp									
Published correlations	Bubble point oil viscosity, cp								
	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0
This work	-24.9	23.1	22.2	0.4	1.4	0.5	-5.9	-3.9	-13.1
Dindoruk and Christman	-24.9	-8.8	-9.7	-23.5	-13.5	-5.7	-0.9	-0.3	-8.1
Petrosky and Farshad	-1.6	10.1	10.7	-9.5	1.5	4.5	3.0	8.9	9.5
Vasquez and Beggs	6.4	13.0	6.5	-11.1	-1.8	-2.8	1.2	8.3	-15.8
De Ghetto, Paone, and Villa	-8.1	5.5	10.4	-10.6	2.2	9.0	4.7	9.0	12.1

Table E-20- A comparison of AARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point oil viscosity less than 1 cp									
Published correlations	Bubble point oil viscosity, cp								
	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0
This work	24.9	27.4	30.2	14.6	13.1	10.7	15.0	16.9	24.9
Dindoruk and Christman	24.9	14.9	27.0	25.0	20.8	22.1	19.6	21.7	21.3
Petrosky and Farshad	5.3	18.1	28.5	16.9	21.4	24.2	22.5	23.4	34.8
Vasquez and Beggs	7.1	18.0	24.9	19.1	22.4	15.8	22.8	30.8	28.6
De Ghetto, Paone, and Villa	9.6	17.4	29.9	19.9	25.2	24.6	21.1	22.5	37.2

Table E-21- A comparison of ARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point oil viscosity between 1 to 10 cp					
Published correlations	**Bubble point oil viscosity, cp**				
	1-2	**2-3**	**3-4**	**4-5**	**7-8**
This work	-29.9	-55.9	-19.8	2.1	1.3
Dindoruk and Christman	-25.5	-54.3	-5.5	18.6	9.6
Petrosky and Farshad	-17.3	-50.0	-11.3	9.3	-13.6
Vasquez and Beggs	-23.9	-54.4	19.5	61.1	-8.0
De Ghetto, Paone, and Villa	-14.8	-46.3	-16.0	-7.5	-31.9

Table E-22- A comparison of AARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point oil viscosity between 1 to 10 cp					
Published correlations	**Bubble point oil viscosity, cp**				
	1-2	**2-3**	**3-4**	**4-5**	**7-8**
This work	32.8	56.7	53.3	4.2	2.1
Dindoruk and Christman	35.0	57.6	44.1	18.6	10.1
Petrosky and Farshad	33.7	51.5	44.6	9.3	15.9
Vasquez and Beggs	34.9	57.1	59.8	61.1	10.4
De Ghetto, Paone, and Villa	32.7	47.0	39.8	7.5	31.9

Table E-23- A comparison of ARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point oil viscosity greater than 10 cp								
Published correlations	Bubble point oil viscosity, cp							
	10-20	21-30	31-40	41-50	51-60	61-70	131-140	141-150
This work	-2.6	-72.3	-40.6	-76.0	-36.4	-80.5	-73.3	-51.1
Dindoruk and Christman	-23.2	-71.1	-58.0	-75.0	-59.4	-77.2	-84.8	-76.8
Petrosky and Farshad	-32.3	-74.8	-66.3	-80.0	-69.0	-84.4	-87.9	-84.3
Vasquez and Beggs	-30.0	-80.5	-76.2	-87.3	-81.3	-84.0	-91.3	-91.3
De Ghetto, Paone, and Villa	-54.7	-79.7	-79.6	-85.5	-84.9	-89.5	-93.8	-94.4

Table E-24- A comparison of AARE in percentage obtained from undersaturated oil viscosity correlation equations regarding bubble point oil viscosity greater than 10 cp								
Published correlations	Bubble point oil viscosity, cp							
	10-20	21-30	31-40	41-50	51-60	61-70	131-140	141-150
This work	61.0	72.3	45.5	76.0	36.4	80.5	73.3	51.1
Dindoruk and Christman	37.6	71.1	58.0	75.0	59.4	77.2	84.8	76.8
Petrosky and Farshad	40.1	74.8	66.3	80.0	69.0	84.4	87.9	84.3
Vasquez and Beggs	47.3	80.5	76.2	87.3	81.3	84.0	91.3	91.3
De Ghetto, Paone, and Villa	54.7	79.7	79.6	85.5	84.9	89.5	93.8	94.4

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